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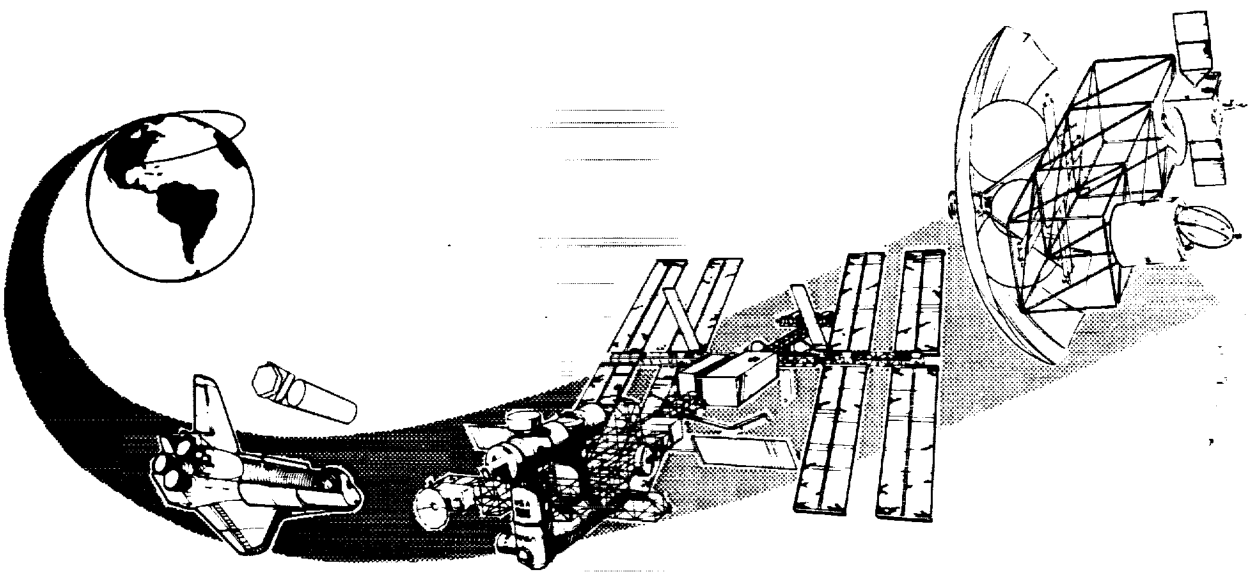

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COMMUNICATIONS SATELLITE SYSTEMS OPERATIONS WITH THE SPACE STATION

VOLUME III – SUPPLEMENTARY TECHNICAL REPORT

January 31, 1988

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ABSTRACT

The NASA Space Station has the potential to provide significant economic benefits to commercial communications satellite operators. The initial reports NASA CR179526 and CR179527 quantified the benefits of new space-based activities and assessed the impacts on the satellite design and the Space Station. This report gives results for the following additional tasks:

1. Quantify the value of satellite retrievability operations and define its operational aspects.

2. Evaluate the use of expendable launch vehicles for transportation of satellites from the earth to the Space Station. (The initial study assumed use of the Space Shuttle only.)

3. Quantify the economic value of modular satellites that are assembled and serviced in space.

The major study results are as follows:

- The newly developed DOMSAT III financial model which explicitly considers satellite system reliability predicts greater benefits for use of the Space Station in the launch of commercial communications satellites. Not only is return-on-investment improved (16.3% vs 9.9%), but also financial risk (defined as the standard deviation of the return-on-investment) is reduced (1.7% vs 4.8%) The financial risk is lower for the Space Station scenario because of the greater overall reliability achieved by use of the Space Station, in particular the greater reliability of the space-based OTV launch versus the solid rocket upper stages of the ELV.

- In-orbit, at the Space Station, and return-to-earth repair scenarios are analyzed with the result that there is no improvement in economic performance (increased rate-of-return or reduced risk) for the particular scenarios considered. In general, space retrieval operations are not financially viable for commercial communications satellites. However, specific "high value" or "easy" cases may still be attractive to retrieve, and thus while retrieval/repair operations are judged to be infrequent, NASA should have capability for retrieval and repair at the Space Station.

- Cost analysis shows that using ELVs in place of the Shuttle changes launch costs, but does not change the value of the APOs compared to business-as-usual ELV delivery to GEO.

- An ELV system is needed to support the Space Station. Additional studies should be initiated as to the feasibility and requirements for an ELV that can dock with the Space Station.

- Three modular satellite designs are analyzed. The result is significantly better economic performance provided that the satellite development and transportation costs are not greatly affected.

- The planned Space Station infrastructure will support on-orbit assembly and servicing. The Integrated Orbital Servicing System should be used for the first generation remote servicing system since the Orbital Spacecraft Consumables Resupply System is too large. A smaller refueling kit or OMV scavenging system should be developed.

- On orbit assembly and servicing can be supported by the Phase II Space Station. However, at least one OMV should be added to the fleet to allow for extended remote operations. Also the fueling platforms should have their own dedicated robotic systems for automated fueling.

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INTRODUCTION

1 Background

The original work on the *Communications Satellite System Operations with the Space Station* Contract is published in two NASA Reports:

- Vol. I – Executive Summary (CR179526)
- Vol. II – Technical Report (CR179527)

This volume is the technical report for three additional tasks that came out of the original study.

2 Previous Work

The focus of the initial study was to identify how the NASA Space Station can provide significant economic benefits to commercial communications satellite operators. Section II of this report describes this work which is summarized below:

- A financial model was developed which describes quantitatively the economics of the space segment of communication satellite systems. The model described the economic status of the system throughout the lifetime of the satellite. The economic performance was given in terms of total capital cost and rate of return on investment.
- The expected state-of-the-art status of communications satellite systems and operations beginning service in 1995 was assessed and described. The results of the assessment were utilized to postulate and describe representative satellite systems.
- New or enhanced space-based activities and associated satellite system designs that have the potential to achieve future communications satellite operations in geostationary orbit with improved economic performance were postulated and defined. These activities included retrieval, upper stage launch with an orbital transfer vehicle, deployment of appendages, checkout, fueling, assembly, and servicing of satellites.

  The financial model was used to determine the economic performance of these different activities and combinations of activities. The use of the space-based OTV to transport satellites from low earth orbit to geostationary orbit offered the greatest economic benefit.
- Three scenarios using combinations of space-based activities were analyzed: (1) a spin stabilized satellite, (2) a three axis satellite, and (3) assembly at the Space Station and GEO servicing. The economic performance of the scenarios was analyzed.
- Functional and technical requirements placed on the Space Station by the scenarios were detailed. Requirements on the satellites were also listed.

The major study results were as follows:

1. Economic benefits are realizable for the commercial communications satellite industry with use of the Space Station.
2. A space-based OTV is necessary to carry out APOs in a timely and cost-effective manner.
3. A study of the economics of retrieval missions and the influence of retrieval on the insurance industry is required in order to

accurately demonstrate the value of retrievability for the satellite.

4. Further NASA-sponsored study of a modular satellite design capable of being assembled in LEO (at the Space Station) and serviced in GEO is required.

5. Space Station hardware required for satellite missions should be installed as soon as possible to demonstrate NASA commitment.

As a result of these conclusions, three additional tasks were added onto the scope of the contract and are these new results are described in this report.

3 Approach

The original technical work was divided into four tasks which are now complete:

1. Develop satellite financial model.
2. Determine economic performance of the business as usual scenario, 1995.
3. Economic assessment of new space-based activities for 1995.
4. Develop Space Station scenarios and requirements.

Three additional tasks were added to the original contract in February 1987:

5. Satellite retrievability study.
6. Impact of the use of expendable launch vehicles.
7. On-orbit assembly and servicing study.

One additional tasks was added to the contract in August 1987:

8. OTV/communications satellite interface requirements.

These eight tasks are summarized below. Only an abbreviated summary is given of Tasks 1 through 4 since they are complete and described in a previous technical report.

3.1 Task 1: Develop Satellite Financial Model

3.1.1 Develop Basic Financial Model

Develop a financial model to describe quantitatively the economics of the space segment of U. S. domestic Fixed Satellite Service (FSS) communication satellite systems. The model describes the economic status of the system throughout the lifetime of the satellite. The model is applicable over the range of satellites expected to be implemented over the next 10 years.

3.1.2 Impact of System Characteristics on Financial Model Output

Identify those Communication satellite system technical and functional characteristics that significantly affect the economic factors used in the model developed in Subtask 1A and the model output values.

3.2 Task 2: Determine Economic Performance of Business as Usual Scenario, 1995

Assess and describe the expected state-of-the-art status of communications satellite systems and operations for U. S. domestic FSS systems initially entering service in 1995. The results of the assessment are used to postulate and describe at least three representative satellite systems.

3.3 Task 3: Economic Assessment of New Space-Based Activities for 1995

3.3.1 Postulate New Space-Based Operations

Postulate and define new or enhanced space-based activities, procedures, and operations (APOs) and associated satellite system designs that have the potential to achieve future communications satellite operations in geostationary orbit with improved economic performance. The availability of the Space Station and its associated systems as projected by NASA will be assumed.

3.3.2 Evaluate the Economics of Space-Based APOs

Establish economic target values or target costs for the APOs postulated in Task 3 that would provide an incentive for their implementation by the industry.

3.4 Task 4: Develop Space Station Scenarios and Requirements

Describe at least two communications satellite system operating scenarios implementing different combinations of the APOs defined in Task 3 through utilization of a low earth orbit Space Station and its supporting equipment and systems.

3.5 Task 5: Satellite Retrievability

The objective of this task is to demonstrate the value of satellite retrievability and to define its operational aspects on the satellite and the Space Station. There are four subtasks:

A. Develop a database of possible communication satellite failure modes, historical failure data, probabilities of failure, and potential repair scenarios. The database will include:

- A list of satellite failure modes including actual failure data.
- Probabilities of failure for each mode.
- An estimate of the feasibility of space or ground repair for each mode.
- Estimates of capital costs for repairs.
- Transportation costs and "fees" for repairs.
- List of most likely failure scenarios.

B. Assess the financial risk for retrieval and non-retrieval scenarios. Calculate the expected financial rates of return and standard deviation of rates of return (financial risk) for the failure scenarios with retrieval and compare to thoses of the non-retrieval scenarios.

C. Determine the impact of satellites having retrieval capability from the insurance industry's business viewpoint. Determine the potential insurance rate reductions, perceptions of increased risk of performing the retrieval operation versus the benefits to be gained, and the possible insistence on all satellites having retrieval capability.

D. Determine the physical and operational requirements on the Space Station imposed by satellite retrieval operations and recommend to NASA changes required in the Space Station infrastructure necessary to accommodate those operations.

3.6 Task 6: Impact of Use of ELVs

The original study tasks 1 through 4 assumed use of the Shuttle. However, recent changes in Shuttle use policy require an evaluation of the use of Expendable Launch Vehicles (ELVs) for transport from earth to the Space Station. There are four subtasks:

A. Identify and characterize existing and planned expendable launch vehicles. Determine the capabilities of all existing and planned, foreign and domestic, launch vehicles that could be used for communication satellite launches from the present to the year 2000.

B. Determine the impact of ELV usage, as opposed to Shuttle usage, on the activities, procedures and operations (APO) scenarios and economics defined in Task 3.

C. Analyze the operational aspects of ELVs as they relate to the APOs and recommend changes that could improve the APO values. Determine how ELV operations would interface with the Space Station.

D. Recommend possible policy procedures for ELV use enabling the APOs in conjunction with the Space Station.

3.7 Task 7: On-Orbit Assembly and Servicing

The objective is to demonstrate the potential economic value of a modular satellite design that could be assembled and serviced in space. There are four subtasks:

A. Formulate a design concept for a modular communications satellite allowing assembly at the Space Station and having servicing capability. Servicing will encompass unscheduled repair operations, routine maintenance, and capability upgrading. Identify ways in which this design may lead to improved service economics.

B. Quantify and evaluate the economic performance of space communications systems employing the modular satellite design and associated operations.

C. Determine the requirements imposed on the Space Station to perform the assembly of the modular satellite and for the Space Station complex to support geostationary servicing operations.

D. Recommend a course of action to be undertaken by NASA that would promote the development and use of modular communications satellites.

3.8 Task 8: Precursor OTV – Communications Satellite Interface Requirements

This task was initiated in August 1987 in order to provide support information to General Dynamics Corporation (GDC). There are three subtasks:

A. Provide the communications satellite requirements needed by the GDC Study *Centaur Operations at the Space Station* (NAS3-24900) for physical interfaces with the Centaur-G Prime, environmental protection, power, and similar items.

B. Use the financial analysis model developed in the Task 1 of the Ford Contract to further define benefits to communications satellite operations of using the OTV, as enhanced by using the Centaur-G Prime as a precursor OTV during the development phase.

C. Participate in two meetings with GDC personnel, one at GDC in San Diego and one at Ford Aerospace in Palo Alto.

Section	Task	Content of Section
I	–	Introduction
II	–	Summary of Previous Work
III	5	Satellite Retrievability
IV	6	Impact of ELVs
V	7	Assembly and Servicing
VI	8	OTV/Satellite Interface
VII	–	Conclusions
A	5A	Satellite Failures
B	6A	Expendable Launch Vehicles
C	5B	Domsat III Model
D	5C	Insurance Interviews

Table I–1: Organization of Report

4 Organization of Report

Table I-1 shows the organization of the report and the correspondence between sections and tasks. Section II gives a summary of the previous work, and Sections III through VI give results for Tasks 5 through 8 respectively. Section VII summarizes the conclusions of the study.

Appendix A contains a database of historical satellite failures and Appendix B contains a database of expendable launch vehicle types and capacities. Appendix C gives a description of the DOMSAT III Financial Model and Appendix D gives results of insurance industry interviews.

Section II
SUMMARY of PREVIOUS WORK

This section gives a summary of the work previously completed and described in NASA CR179526, Vol. I – Executive Summary, and NASA CR179527, Vol. II – Technical Report.

There were three objectives of the initial study:

- Develop a quantitative methodology to assess the viability of a broad range of new space-based activities, procedures, and operations (APOs) when utilized in commercial communications satellite system operations;

- Apply the developed methodology to select which of these APOs can be competitively provided by the Space Station and its associated operating systems; and

- Determine the economic and functional requirements imposed on the Space Station through the provision of these selected APOs.

The technical results are summarized in six subsections:

1. Financial Model

2. Baseline Economic Performance

3. New Space-Based Activities

4. Space Station Scenarios

5. Space Station Requirements

6. Recommendations

1 Financial Model

A communications satellite financial model (the Financial Model) that describes quantitatively the economics of the space segment of U. S. domestic fixed satellite service communication satellite systems was developed by Coopers & Lybrand under subcontract to Ford Aerospace. (Ground terminals and terrestrial system costs are excluded from consideration except for satellite telemetry, tracking, and control systems.)

The Financial Model describes the economic status of the system throughout the lifetime of the satellite beginning with its design and continuing through its construction, launch, and commercial operations. It can be applied to the range of satellite sizes, communications payloads, and lifetimes expected to be implemented in the 1985 to 1995 time frame.

The Model was calibrated by analysis of three 1985 satellite systems and validated by comparison with actual satellite system economic performance. Significant satellite system characteristics were identified and a sensitivity analysis of the impact on system economic performance was performed.

2 Baseline Economic Performance

2.1 Definition of 1995 Systems

The economic performance for the following four 1995 satellite types was analyzed:

- Ku-band spin-stabilized satellite;

- Ku-band 3-axis satellite;

- Hybrid (C and Ku-bands) 3-axis satellite;

- Large Ku-band 3-axis satellite.

Table II-3 summarizes the characteristics of the four satellites.

2.2 Economic Performance

Tables II-1 and II-2 give the economic performance of the 1995 baseline satellites. The initial rates-of-return were adjusted to account for a postulated 33% transponder price reduction from 1985 to 1995. Capital costs are stated in 1985 dollars and are the total of all costs associated with building and launch of the satellite.

Table II-1 gives the dual terminal rate-of-return (DTRR) for the four satellite types that are analyzed. (See Volume II, Technical Report, Subsection II-3.3 for an explanation of DTRR.) The 1985 column gives the Financial Model results for the 1985 launch satellites with a basic transponder price of $1.9 M per year (C-band, 5.5 W, 36 MHz bandwidth).

The "initial" 1995 returns are for the 1995 satellite designs (50% more capacity) and the same basic transponder price. The "final" 1995 returns were adjusted 4.4 points lower so that the average return equals the average 1985 return. This required a 33% decrease in basic transponder price.

The Large satellite is a 1995 design. Its "initial" and "final" returns are 29.6% and 25.1% respectively. The higher return implies that transponder prices could be further reduced.

Table II-2 gives the capital costs of the baseline satellites. The greater costs of the 1995 satellites are due to the increased number and power of the transponders.

Satellite Design	DTRR Return, %		
	1985	1995	
		Initial	Final
C/Ku Spinner	18.1	23.4	18.9
Ku 3-axis	19.8	23.3	18.8
Hybrid 3-axis	21.9	26.5	21.9
Large 3-axis	–	29.6	25.1

Table II–1: DTRR for Satellite Systems

Satellite Design	Capital Cost, $ M	
	1985	1995
C/Ku Spinner	76.5	115.1
Ku 3-axis	104.3	116.8
Hybrid 3-axis	83.1	138.8
Large 3-axis	–	215.4

Table II–2: Capital Costs for Satellites

2.3 Discussion of Economics

There is little to choose between the capital costs and rates of return for the spinner and 3-axis Ku-band systems. However, due to its greater number of transponders, the hybrid system has a 3% greater rate of return.

This is achieved without selling any cross-connected transponders; i.e. transponder prices are based on all C and all Ku-band sales. As discussed in Subsection III-4.8 of the Technical Report, sales of hybrid pairs of transponders bring a 30% premium and would further increase the return. For the purposes of this analysis, we take the conservative assumption that revenues from sales of hybrid pairs will be offset by a decrease in utilization of the remaining "wrong way" pairs.

The impressive results for the large satellite are due to economies of scale. The implication is clearly that this is the satellite design of the future. An 18% transponder price reduction from the best performing 1995 satellite is achieved, and a 45% price reduction from the 1985 satellite systems.

3 New Space-Based APOs

3.1 Postulation of APOs

New or enhanced space-based Activities, Procedures, and Operations (APOs) and associated satellite system designs that have the potential to achieve future communications satellite operations in geostationary orbit with improved economic performance have been defined.

The criteria for selection of the APOs are increased communications satellite technical and

	Spinner	Ku-Band	Hybrid	Large
Baseline satellite	Hughes 393	RCA K2	Ford FS-1300	Hectosat
Design life (yr)	10	10	10	10
BOL mass (kg)	1377	1044	1540	2144
Payload mass (kg)	261	261	342	747
– Antenna (kg)	29	29	52	161
– Transponder (kg)	232	232	290	586
EOL power (W)	2900	3000	4200	3100
Stabilization	Spin	3-axis	3-axis	3-axis
Frequencies	Ku-band	Ku-band	C/Ku-bands	Ku-band
Number of transponders:				
– C-band			24	
– Ku-band	24	24	24 & 6	108
Transponder bandwidth:				
– C-band (MHz)			36	
– Ku-band (MHz)	54	54	36 & 72	36
Transponder power:				
– C-band (W)			10	
– Ku-band (W)	50	50	35	20
Antenna coverages:				
– C-band			2	
– Ku-band	3	3	3	9
Satellite EIRP (Conus):				
– C-band (dBW)			36	
– Ku-band (dBW)	46	46	46	46
Launch vehicle(s):	Ariane 4 STS/PAM D2	Ariane 4 STS/PAM D2	Ariane 4 STS/Ford	Ariane 4 STS/IUS
Satellite Cost ($M, 1985)	54.2	50.9	64.6	88.1

Table II–3: Summary of 1995 Satellite Characteristics economic performance. The selection of APOs is made based on predicted available technology and judgment of economic value. There were eleven APOs considered.

1. Emergency retrieval from LEO
2. Ground-based orbital transfer vehicle (OTV) launch to geostationary transfer orbit (GTO)
3. Ground-based OTV launch to geosynchronous earth orbit (GEO)
4. Deployment of appendages at shuttle
5. Space-based OTV launch to GTO
6. Space-based OTV launch to GEO
7. Deployment of appendages at Station
8. Checkout at Space Station
9. Fueling at Space Station
10. Assembly at Space Station
11. Servicing/replacement for GEO satellites
    - Transport to low earth orbit (LEO) for servicing
    - Servicing in GEO

The APOs are listed in order from simplest to most complex, which is approximately the same as chronological for availability.

3.2 Economics of APOs

The Financial Model was used to analyze the economics of the individual and combination APOs for the 1995 spinner and 3-axis hybrid satellite designs. Table II-4 gives a summary of APO economic performance.

The APO value is defined as the "fee" NASA could charge for the APO that would result in the same economic performance as for the business-as-usual scenario. The major influences on economic value are the following:

- Savings in STS launch costs due to decrease in mass.
- Savings in insurance costs (20% nominal rate).
- Increase in satellite cost.

The combination APOs have an additional value due to the fact that some of the same satellite equipment is required for different APOs.

The conclusion is that use of the space-based OTV for transport of two or more 3-axis satellites from LEO to GEO is the high value APO that can make commercial satellite operations with the Space Station a reality. Once at the Space Station, other APOs of marginal value but important to the particular mission can be done.

4 Space Station Scenarios

Three communications satellite system operating scenarios implementing different combinations of APOs are analyzed. The economic performance of these scenarios is evaluated and compared to the baseline performance. Finally the sensitivity of the results to different insurance and launch cost assumptions is analyzed.

The following scenarios are chosen for evaluation:

- Spinner satellite scenario:
- 3-axis satellite scenario:
- Assembly/servicing scenario:

The spinner satellite APO scenario is not economically attractive but is included for completeness. It is our belief that satellites will have a 3-axis design in order to best utilize the capabilities of the Space Station.

The assembly/servicing scenario requires a completely new satellite design which will not evolve until the Space Station is in orbit. Its IOC (initial operational capability) is unlikely to be 1995 but rather the year 2000.

4.1 Spinner Satellite Scenario

The following APOs are utilized with the 1995 spinner satellite design:

- Checkout at Station

APOs at Shuttle	Spinner Satellite ($115 M)			3-Axis Satellite ($139 M)		
	Value	$M	Major Reasons	Value	$M	Major Reasons
Capability for LEO Retrieval	yes	1.1	Insurance -1%	yes	1.3	Insurance -1%
GB-OTV from LEO to GTO	yes	12.5	Insurance -2%	–	–	LEO-GEO better
GB-OTV from LEO to GEO	–	–	Spinner design	yes	37.2	Insurance -5%
Deploy appendages	no	–	Spinner design	yes	1.7	Insurance -1%
3-Axis Combination	–	–		yes	38.8	STS cost/Ins. -6%

APOs at Space Station	Spinner Satellite ($115 M)			3-Axis Satellite ($139 M)		
	Value	$M	Major Reasons	Value	$M	Major Reasons
Capability for LEO Retrieval	yes	.5	Insurance -1%	yes	.7	Insurance -1%
SB-OTV from LEO to GTO	yes	13.0	Insurance -2%	–	–	LEO-GEO better
SB-OTV from LEO to GEO	–	–	Spinner design	yes	39.5	Insurance -5%
Deploy satellite appendages	no	–	Spinner design	no	–	Sat. cost increase
Checkout of satellite	no	–	Spinner design	no	–	Sat. cost increase
Add fuel to satellite	no	–	Spinner design	no	–	Sat. cost increase
Capability for GEO Retrieval	no	–	Sat. cost increase	yes	1.3	Insurance -1%
Spinner Combination	yes	15.9	STS cost/Ins. -6%	–	–	
3-Axis Combination	–	–		yes	41.2	STS cost/Ins. -9%

Table II–4: Summary of APO Economics

- Fueling at Station
- Space-based OTV to GTO
- Retrieval capability from GEO

Table II-5 gives a comparison of the capital expenditures for the spinner scenario with the Space Station compared to the baseline spinner scenario. The OMV/OTV fees are for use of the Orbital Maneuvering Vehicle and the Orbital Transfer Vehicle. A total insurance benefit of 6 points is hypothesized for this scenario. Launch insurance is 20% for the baseline case and 14% for the Space Station scenario. Insurance appears twice in the table, first for the upper group of capital expenditures and second for the lower group.

The result is a $3.5 M savings for the scenario versus the baseline satellite. The Financial Model indicates this corresponds to a 0.2 point increase in the rate-of-return (DTRR) from 18.9% for the baseline to 19.1% for the spinner scenario with the Space Station. Considering

Capital Expenditure	Cost ($M 1985) Baseline	Station Scenario
Satellite	54.3	56.9
STS Launch	29.9	21.1
Perigee stage	3.8	.7
Launch support	1.6	1.6
Mission ops.	2.6	2.3
Insurance	23.0	13.5
Total	115.1	96.1
OMV/OTV	–	10.3
Station support	–	3.0
Insurance	–	2.2
Total	115.1	111.6

Table II–5: Spinner Scenario Economics

the uncertainties in the inputs to this calculation, this scenario has marginal value.

4.2 3-Axis Satellite Scenario

The following APOs are utilized with the 1995 hybrid 3-axis satellite design:

- Deploy appendages at Station
- Checkout at Station
- Fueling at Station
- Space-based OTV to GEO
- Retrieval capability from GEO

Table II-6 gives a comparison of the capital expenditures for the 3-axis scenario with the Space Station compared to the baseline 3-axis scenario. A total insurance benefit of 9 points (a rate change from 20% to 11%) is hypothesized this scenario. Space Station support costs for handling, deployment, checkout, and fueling are estimated.

The result is a $21.5 M savings for the scenario using the Space Station versus the baseline case. The Financial Model indicates this corresponds to a 1.4 point increase in the rate-of-return (DTRR) from 21.9% for the baseline to 23.3% for the 3-axis scenario with the Space Station. This indicates substantial economic value.

Capital Expenditure	Cost ($M 1985) Baseline	Station Scenario
Satellite	64.6	62.5
STS Launch	35.4	16.1
Perigee stage	6.9	.6
Launch support	1.6	1.6
Mission ops.	2.6	1.6
Insurance	27.8	10.2
Total	138.8	92.6
OMV/OTV	–	18.5
Station support	–	3.5
Insurance	–	2.7
Total	138.8	117.3

Table II–6: 3-Axis Scenario Economics

4.3 Assembly/Servicing Scenario

The following APOs are utilized with the 1995 hybrid 3-axis satellite payload that is incorporated into a redesigned satellite:

- Assemble satellite at Space Station
- Checkout at Space Station
- Fueling at Space Station
- Space-based OTV to GEO
- Service satellite in GEO

In order to be serviced in orbit by an Orbital Maneuvering Vehicle (OMV) plus servicer front end, the satellite must be designed in a different manner. The concept is to have a satellite design with modules that are replaced during servicing. This leads to a less highly integrated satellite design that consists of pieces that can be transported separately and then assembled at the Space Station. Thus the concept of servicing a satellite leads to the potential for assembly.

The servicing mission is planned to occur after nine years and to result in extension of the satellite life by another nine years. The modular satellite design would be 10% heavier than the baseline satellite of the same capacity. The servicing mission would replace 40% of the mass of the modular satellite.

Table II-7 gives a comparison of the capital expenditures for an 18 year assembly/servicing scenario with the Space Station compared to a baseline scenario with two successive hybrid 3-axis satellite launches each having a nine year lifetime. The baseline scenario uses the 1995 3-axis hybrid satellite with 9 year lifetime and scenario per Subsection VIII-3 of the Technical Report. It is assumed that the second satellite has the same cost as the first. The insurance rate is assumed to be the same (11%) for assembly/servicing scenario as for the baseline case.

The initial capital expenditure is $10 M more but the second launch is $45 M less than the baseline approach. The Financial Model gives a

Capital Expenditure	Cost ($M 1985) Baseline 1st or 2nd	Scenario 1st	2nd
Satellite	62.5	68.9	34.8
STS Launch	16.1	15.4	8.0
Perigee stage	.6	.6	.3
Launch support	1.6	1.6	.5
Mission ops.	1.6	1.6	1.6
Insurance	10.2	10.9	5.6
Total	92.6	99.0	50.8
OMV/OTV	18.5	19.9	16.5
Station support	3.5	5.0	3.0
Insurance	2.7	3.1	2.4
Total	117.3	127.0	72.7

Table II–7: Assembly/Servicing Economics

3-Axis Satellite	Cost ($ M)	Rate-of-return (%)
Baseline (20%)	138.8	21.9
Scenario (11%)	117.3	23.3
Scenario (20%)	130.5	22.5

Table II-8: Influence of Insurance Rate

Cost Change	Cost ($M 1985) Baseline	Scenario	Delta
Original case	138.8	117.3	21.5
OTV plus 50%	138.8	127.7	11.1
STS minus 50%	116.7	108.3	8.4
OTV minus 50%	138.8	106.9	31.9
STS/OTV -50%	116.7	97.9	18.8

Table II–9: Influence of Launch Costs

rate-of-return (DTRR) approximately the same for this scenario as for the baseline (21.07% versus 21.10%).

The conclusion is that the economics of the assembly/servicing scenario are less favorable than launching two successive conventional satellites with the OTV. However, our satellite costs derived using Price H are based on a very preliminary design of a assemblable, serviceable satellite. We recommend that more work be done on design of such a satellite. In particular, relaxation of constraints on compactness may lead to substantial savings in integration and test costs.

4.4 Sensitivity Analysis

4.4.1 Launch Insurance

The important point is the difference, if any, between the Space Station scenario and the baseline case insurance rate. The scenarios assume a 6 point and a 9 point difference respectively for the spinner and 3-axis scenarios.

If it is assumed there is no difference in insurance rates due to the scenarios, the cost of the spinner scenario increases by $8.3 M to $119.9 M, versus $115.1 M for the baseline. The 3-axis scenario increases in cost by $13.2 M to $130.5 M, versus $138.8 M for the baseline.

The conclusion is that without insurance benefits the spinner scenario is definitely not viable. The 3-axis scenario continues to show benefits, although reduced greatly from $21.5 M to $8.5 M. Table II-8 summarizes the satellite cost and rate-of-return (DTRR) changes for the 3-axis scenario with 20% insurance rate.

4.4.2 Launch Costs

Table II-9 summarizes the effects of some substantial changes in launch charges on system costs. The baseline and 3-axis scenario costs are compared for each launch cost assumption. The scenario continues to show value regardless of the launch cost change. The economics are very sensitive to changes in OTV costs. The assumption of STS charges being reduced by 50% also has a large negative effect on scenario economics.

4.5 Conclusions

The spinner scenario has a small nominal value with the hypothesized costs, but is sensitive to changes in insurance and launch costs. This scenario is judged to be not economically viable.

The 3-axis scenario shows substantial value which continues to be positive under worst case insurance and launch cost assumptions. This scenario is judged to be economically viable.

The assembly/servicing scenario has equal value to two successive launches of the 3-axis scenario. Considering our relatively crude analysis of the satellite design, we believe this scenario has promise of better performance and should be analyzed in more detail.

5 Space Station Requirements

5.1 Hardware Requirements

5.1.1 Servicing and Storage Bay

The primary requirement on the Space Station is the inclusion of a servicing/storage bay in the initial design. An early servicing bay would be used for unscheduled retrieval missions where a perigee motor or ELV upper stage fails, leaving the satellite in an orbit not accessible to the OMV.

The economic and environmental advantages of retrieval missions to the Space Station justify the initial inclusion of this area. The servicing/storage bay would later be used for storage of satellites prior to using the OTV and for storing and assembling small satellites.

The storage bay should be large enough to accommodate up to four 1995 satellite designs for storage and an additional area for servicing. A 10 m x 10 m x 20 m volume should be sufficient. The bay should be enclosed for micrometeorite and passive thermal protection which can be augmented by internal satellite thermal systems. In addition, standard power and communications ports should be available so that satellites can use Space Station power and can be monitored from inside the manned modules. Power consumption is expected to be in the range of 10 W to 400 W per satellite and data rates are low (1200 b/s).

The servicing/storage bay should be located near the OTV facility and other transportation nodes for the Shuttle and OMV. Since the MRMS (mobile remote manipulator system) transfer systems are predicted to be slow, the time of transfer becomes a concern for the power, thermal, and telemetry systems. Increasing satellite batteries for this procedure should be avoided. Another issue is the mechanical vibrations and oscillations during satellite transfer, which may affect other operations requiring a stable environment.

5.1.2 Automated Transfer Facilities

A universal retention system should be developed to reduce the required hardware weight on satellite systems, and allow automated docking and release.

Automated systems such as the MRMS (mobile remote manipulator system) are needed to transfer satellites and equipment to and from the Shuttle, OTV, OMV, and storage/servicing bay. Systems with a high level of articulation and control are desired to reduce demand for extra vehicular activity (EVA) such as deployments and connections.

5.1.3 Fueling Facilities

Fueling facilities may be required at the Space Station. Although there is no economic advantage for fueling at the Space Station, other factors such as Shuttle launch safety may require it, as may APOs such as assembly. The issues surrounding fueling should be examined in depth before placing requirements on the Space Station.

5.2 OMV Requirements

The initial use of the Orbital Maneuvering Vehicle (OMV) is as a space tug to retrieve stranded satellites from LEO as well as transfer cargo from expendable launch vehicles (ELVs) to the Space Station. This requires space-basing of an OMV in order to be available for unscheduled events such as emergency retrieval.

The OMV would need to be attachable to a servicing device such as the Smart Front End for GEO servicing. This combination should have the capability of servicing several satellites on each mission. Methods for changing out modules should be standardized and tested in LEO prior to use in GEO.

There should be at least two OMVs in order to be able to retrieve a malfunctioning OMV to the Space Station for repair.

5.3 OTV Requirements

The use of the Orbital Transfer Vehicle (OTV) gives the largest economic advantage of the APOs evaluated. The requirements placed on the OTV by this study are within the scope of the capabilities required by the initial OTV studies. Several satellites must be launched at once in order for the relatively large capacity OTV to be economical. This requires a multiple payload carrier (MPC) which should use a standard retention system compatible with the Space Station servicing bay.

The OTV should provide power and telemetry links to the satellite while in transit. Slow spinning of the OTV will assist in maintaining the thermal environment of the satellites.

The OTV should be capable of maintaining accelerations of 0.1 G or less to allow appendage deployment at the Space Station. This feature would also be required for large communications antennas and platforms not covered in this study.

There should be at least two OTVs in order to be able to retrieve a malfunctioning OTV to the Space Station for repair. An OTV based at the Space Station is preferred to the ground-based alternative in order to respond more rapidly to an emergency retrieval.

5.4 Operations and Policy

There are other requirements that the satellite communications industry places on the Space Station infrastructure beyond hardware or scarring needs. It is important that scheduled use of the Space Station, OMV, or OTV not be interrupted. Many of the APOs using the Space Station will have no alternative if the service is delayed due to higher priority government missions. The Space Station should adopt a set of operations and policies that insure its users a high degree of reliability.

The procedures required on the ground for Space Station safety should become streamlined without hindering the determination of safeness. Present NASA safety requirements for the Shuttle require a large amount of paperwork and additional test time prior to launch. The safety requirements for the Station should be studied far in advance so that an efficient safety regulation program can be utilized.

Space Station policies should be devised so that termination of services will not occur without sufficient lead time to allow satellite manufacturers to phase Space Station APOs out of their designs. Reduction of services due to safety or accidents should not be placed only on the commercial users.

6 Recommendations

6.1 Need for Space-Based OTV

The space-based Orbital Transfer Vehicle (OTV) is recommended rather than a ground-based OTV for several reasons. Most important is minimization of possible scheduling problems. Operations based at the Space Station such as deployment and assembly would need to be scheduled simultaneously with the ground launch of the ground-based OTV. Delays occurring on the ground (for example, due to weather) could disrupt schedules at the Station due the necessity for preparing and protecting multiple satellites. Conversely, satellite operation delays at the Station could delay the ground launch. The ground-based OTV, if fueled, requires a large amount of power to prevent cryogenic boil-off losses.

Another reason for recommending a space-based OTV is risk. Requiring a ground launch for every OTV launch adds risk to the system which could affect the insurance advantage associated with the OTV.

A concern raised by this study is the operational aspect of interfacing a ground-based OTV with the Station and a return vehicle such as the Shuttle. The logistics and cost of returning, refurbishing, and relaunching an OTV have not been determined. A fueling system of a space-based OTV could possibly be simplified by using ground launched tanks that could be "snapped" into the OTV in space. This concept could decrease the cost of launching and retrieving the entire OTV, and may be more cost effective than scavenging systems with long term space-based fueling depots.

The final OTV issue is the cost comparison between space-based and ground-based operation. The obvious advantage of space-basing is that the OTV structure does not need to be carried from Earth to LEO for each mission. As shown in the sensitivity analysis of Subsection VIII-5 and discussion of launch costs in Subsection VII-2.3 of the Technical Report, economics are very sensitive to launch cost assumptions. Perhaps future reduction in launch costs will make this point academic. A careful analysis of OTV costs is needed.

The feasibility of many APOs may be impacted adversely by use a ground-based OTV due to operational constraints.

6.2 Study of Retrieval Missions

The economics of retrieval missions is discussed in Subsection VII-5 of the Technical Report. There can be substantial benefits in retrieval missions and we see this to be a natural function of the Space Station from its position as a "gateway to space" and transportation node.

We recommend that NASA sponsor a study of the economics of retrieval missions and the influence of retrieval on the insurance industry. The goals of this study would be to more accurately demonstrate the value of retrievability for the satellite and to more closely define the operational aspects of retrievability on the Space Station and the satellite.

Involvement of insurance company representatives in the study is desirable, along with a methodology to assess financial risk (defined as the standard deviation in the rate-of-return) for different retrieval scenarios.

6.3 Modular Satellite Design Study

A modular satellite design is required for implementation of assembly and servicing scenarios. We recommend that NASA sponsor a study in this area in order to stimulate the satellite manufacturing industry to consider these designs.

A future NASA or government satellite should then incorporate a requirement for serviceability and/or assembly in order to demonstrate feasibility.

6.4 Study of ELV Use

NASA has recently said that commercial launches will be phased out of the Shuttle program. Expendable Launch Vehicles (ELVs) will need to be used for transport from Earth to LEO (near the Space Station), instead of using the Shuttle as assumed in this study. There are potential impacts on launch costs and risks, on the APOs, and on the requirements placed on the ELV system.

A study is needed to determine the effect that launching commercial communications satellites to LEO on ELVs would have on the APOs, and the requirements placed on the ELVs. The ELV system needs to be designed to supply regular and reliable transportation form Earth to Space Station in order to facilitate the APOs.

6.5 Technology Developments

The following technology developments are recommended:

- Modular satellite designs
- OTV with low thrust and based in space
- RF interfaces for assemblable satellite
- Telerobotics for IVA operations and servicing

6.6 Purpose of Space Station

We see the highest use of the first Space Station as a transportation node with associated staging and assembly areas. Some requirements like safety are of continuing concern, but the inappropriate placing of instruments or experiments on the initial Station that place further difficult requirements is to be avoided.

The value of the Space Station as transportation node will vanish if it is too difficult to use. The commercial sector will not use something that places additional financial risks on the operations, such as time delays in on-orbit operation. For instance, a one month launch delay is equivalent to 0.4% rate-of-return (DTRR) or $5 M initial cost.

Section III
SATELLITE RETRIEVABILITY

The problem is to demonstrate the value of satellite retrievability and to define its operational aspects on the satellite and the Space Station. The initial study results showed that under certain conditions there is high value in retrieving and repairing failed satellites in space. This follow-on work uses a more sophisticated analysis to assess economic performance and risk of various retrieval scenarios. The work is organized as follows:

1. Previous Work
2. Satellite Failure Database
3. Domsat 3 Financial Model
4. Transportation Scenarios
5. Baseline Satellite Design
6. Economic Analysis
7. Impact on Insurance
8. Requirements on Station
9. Conclusions

1 Previous Work

Previous work on retrieval missions reported in the February 1987 Technical Report (NASA CR-179527), Subsection VII-5, can be summarized as follows:

- The cost of making a communications satellite retrievable is low:
  - \$1.3 M versus \$115 M spinner satellite in-orbit cost (1.1%).
  - \$1.1 M versus \$139 M 3-axis satellite in-orbit cost (0.8%).
  - These figures do not include the cost of making the satellite more easily repairable or the cost of the repair.
- Probabilities of a retrievable failure (satellite is non-operational but intact) are 8% of all launches based on historical data.
- Cost of retrieval operation is dominated by transportation and insurance costs:
  - Return of entire satellite to earth for repair is usually too expensive.
  - Repair in space (if possible) has a potentially large economic value.
- Previous analysis was based on the assumption of breakdown and a fixed mission scenario.
- A more versatile analysis tool is needed to assess probabilities of different missions and to evaluate the financial risk – defined as the standard deviation of the rate of return on investment.

Figures III-1 and III-2 summarize retrieval scenario costs. For LEO retrieval – repair – relaunch scenarios, \$9 M is estimated for repair at the Space Station versus \$95 M for earth repair. For GEO retrieval – repair – relaunch scenarios, \$85 M (OTV) is estimated for Station repair versus \$149 M for earth repair.

The conclusion of this "static" analysis is that in-space repair can have high value (i.e. costs significantly less than the value of the satellite), while return-to-earth for repair is not cost-effective for GEO satellite failures, and is

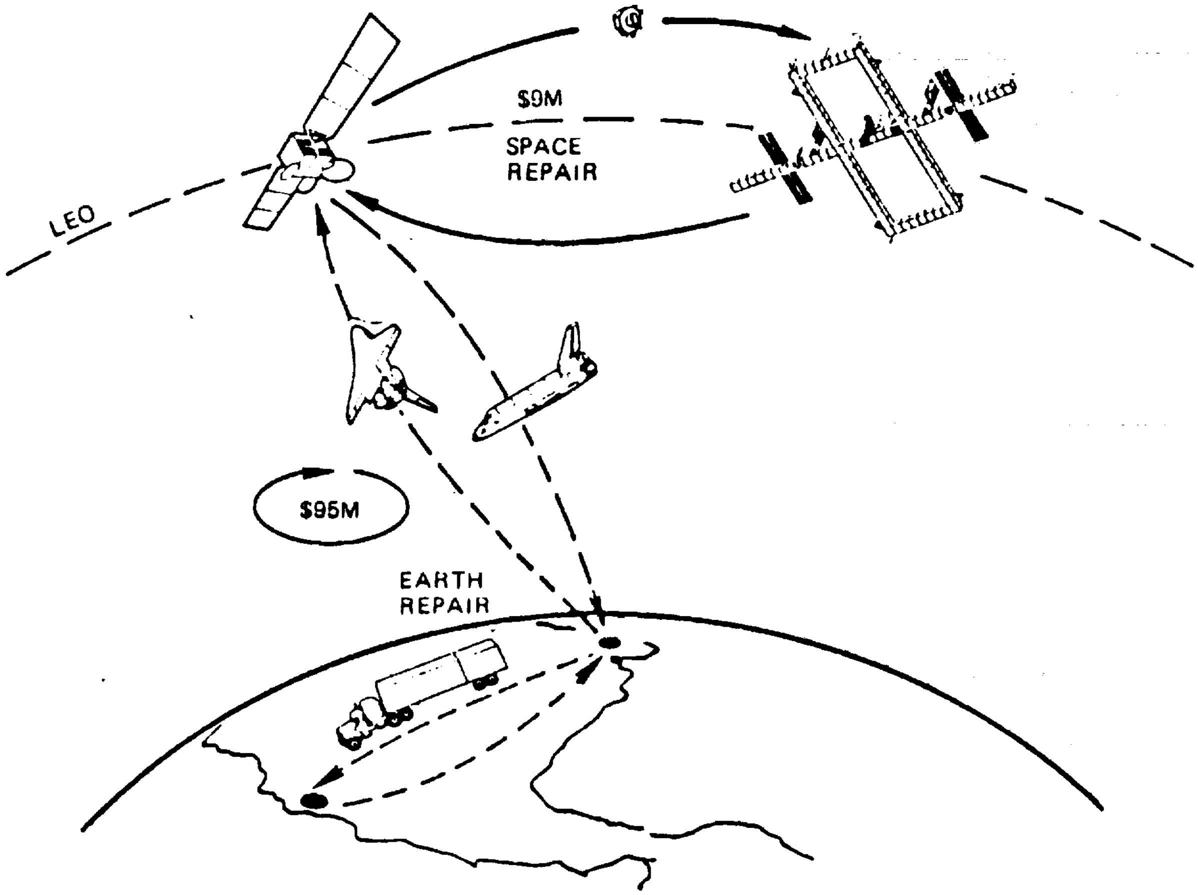


Figure III–1: Low Earth Orbit Retrieval Scenarios: Cost Estimates

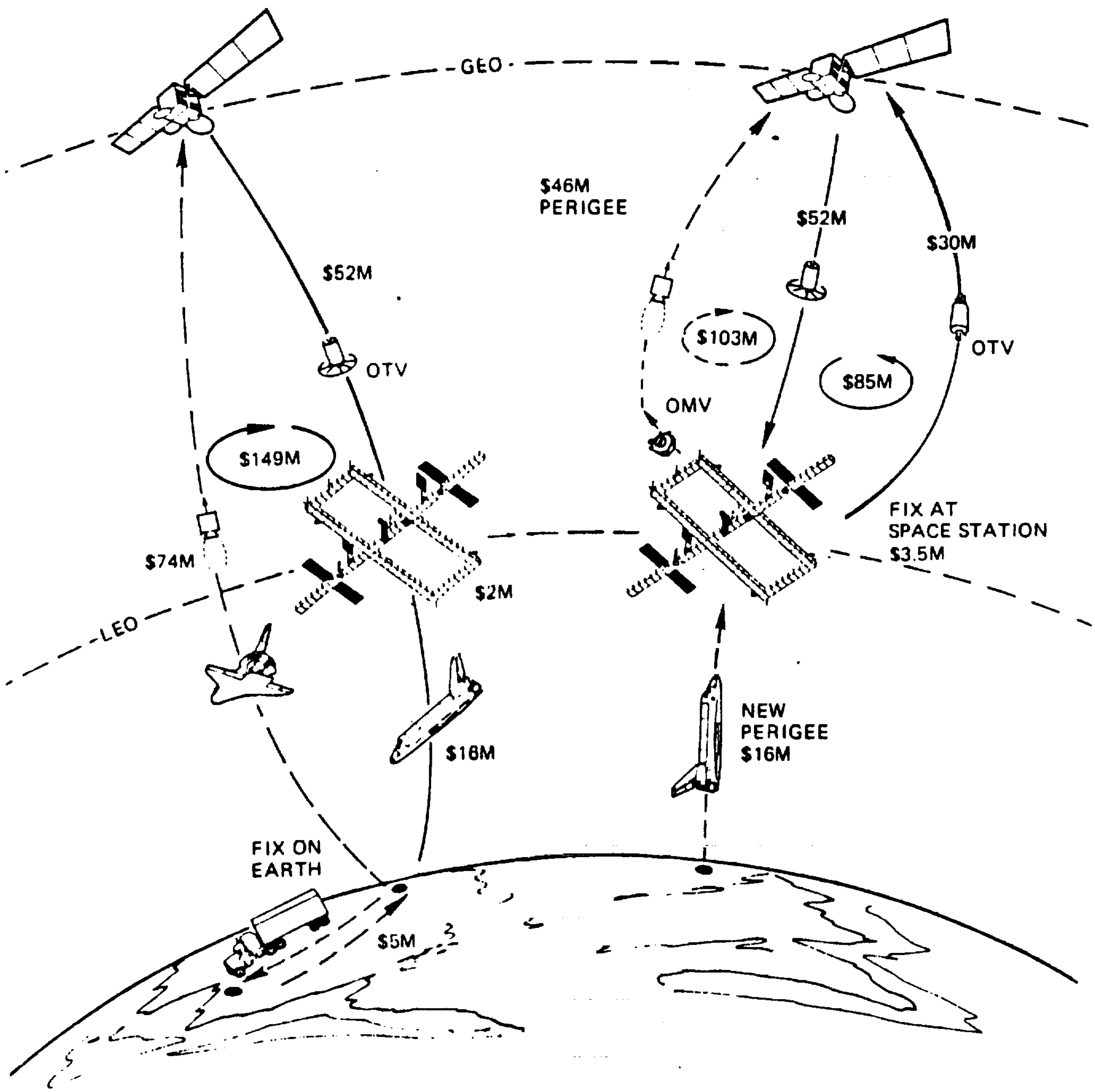


Figure III–2: Geosynchronous Orbit Retrieval Scenarios: Cost Estimates marginally possible for failures in LEO. However, a more sophisticated analysis of the retrieval problem is required, and is the subject of this Section.

There is an interplay between probability of failure (which also determines insurance rates), satellite cost, launch cost, and retrieval mission costs which can only be analyzed via a probabilistic model. For example, if there are few or no retrievable and repairable failures, there is little value in retrieval. Another extreme case is when transportation costs are very high or very low, both of which favor retrieval – either to allow in-space repair and reduce relaunch costs or to save on replacement satellite costs.

2 Satellite Failure Database

Table III-1 summarizes the data given in Appendix A on historical communication satellite failure rates and probabilities of failure. The failures are classified into five categories:

1. Initial launch stage
2. Upper launch stage(s)
3. Apogee kick motor
4. Satellite before initial operation
5. Satellite after initial operation

Note that the bulk of failures (70%) occur in the launch stages (first three categories). For the years 1977 through 1986, the failure rate was 17 out of 98 or 17% of the geosynchronous communications satellites launched.

Table III-2 partitions the failure statistics into "repairable" (those failures that could be retrieved and repaired at the Space Station) and "mission lost" (non-repairable). Note that these failure statistics and this classification applies to satellites launched from the ground direct to orbit (i.e. they do not use the Space Station).

Table III-3 estimates the failure statistics for communications satellites launched via the Space Station. The estimated total failure rate is lower (11% versus 17%) due to the use of a more reliable OTV, deployment of appendages at the Space Station, and checkout at the Space Station. However, the relative amount of failures judged to be repairable goes down due to the fact that initial operations at the Space Station would have eliminated the easily fixed problems.

Type of Failure	Failures as a Percentage of	
	Failed launches	All launches
Initial launch stage	12	2.0
Upper launch stage(s)	29	5.1
Apogee kick motor	29	5.1
Sat. before checkout	12	2.0
Sat. after checkout	18	3.1
Totals	100	17.3

Table III–1: Historical Failure Statistics

3 Domsat III Financial Model

Appendix C gives a description of the DOMSAT III financial model developed by *Princeton Synergetics*. A summary is as follows:

- It is a Monte Carlo model which runs many cases in order to take into account the probabilities of different events in a scenario. The results are based on the probabilities and costs of the different outcomes of the mission.
- Inputs to the Model:
  - The mission is broken down into segments with probability of success and cost for each segment.
  - Insurance is based upon expected loss times a multiplier (1.2) to allow for overhead. (The expected loss is based on the input probability of success for each operation and the failure/recovery paths.)
- Operation of Model:
  - A mission model is selected: (i.e. initial launch of three satellites and re-

Failure Category	Probability of Failure (%) Repairable Failure	Mission Lost	Total Failures
Initial stage failure	.0	2.0	2.0
Perigee stage failure	2.8	2.3	5.1
Apogee motor malfunction	3.6	1.5	5.1
Satellite failure (before IOC)	1.4	.6	2.0
Satellite failure (after IOC)	2.9	.2	3.1
Totals	11.7	6.6	17.3

Table III–2: Estimate of Repairable and Non-Repairable Failures (Earth→GEO Launch)

Failure Category	Probability of Failure (%) Repairable Failure	Mission Lost	Total Failures
Earth to Station	1.0	6.0	7.0
OTV to GEO	1.0	.0	1.0
Satellite failure (before IOC)	.5	.5	1.0
Satellite failure (after IOC)	1.0	1.0	2.0
Totals	3.5	7.5	11.0

Table III–3: Estimate of Repairable and Non-Repairable Failures (Launch Via Space Station) trieval – repair at the Space Station for repairable failures).

- 1,000 different cases of each scenario are run. An independent choice of success or failure for each mission segment is made based on the input probability of success of each operation.
- The result of each case is the rate of return on investment.
- The standard deviation of the rate of return around the mean rate of return for all cases is a measure of the financial risk.

- Results:
  - The mean rate of return (also referred to as the expected internal rate of return or IRR) must be high enough to justify the mission.
  - If the standard deviation of the rate of return is high, the mission is risky; if it is low, there is low economic risk.

4 Transportation Scenarios

A number of non-retrieval and retrieval cases based on different transportation scenarios will be analyzed and compared. The transportation scenarios used for analysis of the retrieval cases are illustrated in Figures III-3 through III-7 (also described and illustrated in Appendix C). Two transportation scenarios are used for each case: one for initial payload (P/L) placement operations and the other for P/L maintenance/repair operations.

It is assumed that a transportation system consists of a generic launch vehicle (LV) that contains two stages (LVS1 and LVS2) and a generic orbital transfer vehicle (OTV). (Each of these stages may actually contain other stages but can be considered from a reliability, cost and recovery point of view as being lumped into a single stage.)

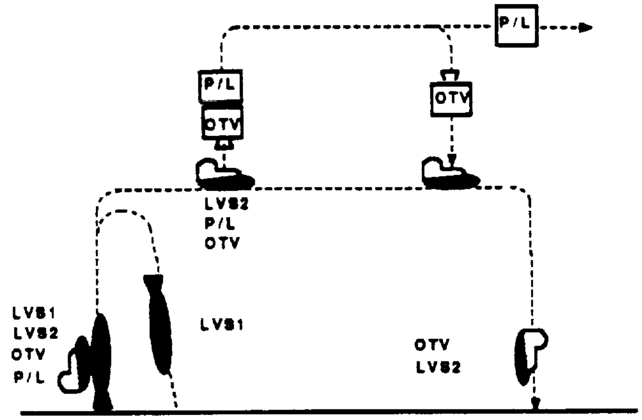


Figure III–3: Transportation Scenario 1: Direct Placement Using Ground-Based Assets

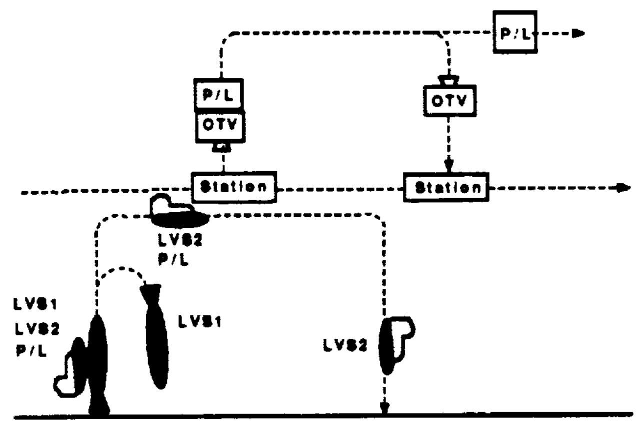


Figure III–4: Transportation Scenario 5: Direct Placement Using Space-Based Assets

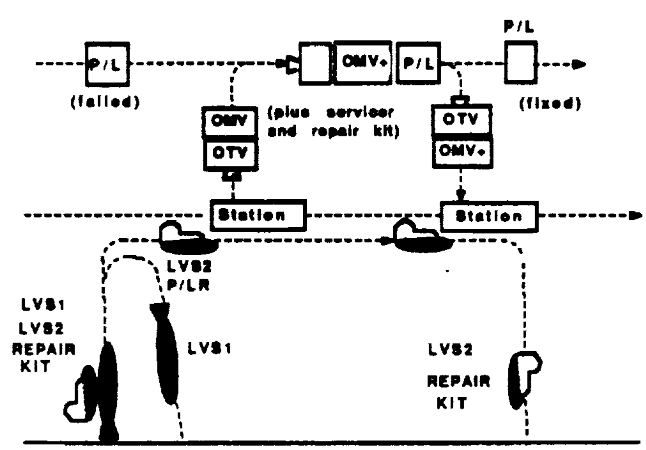


Figure III–5: Transportation Scenario 7: On-Orbit Repair Using Space-Based Assets

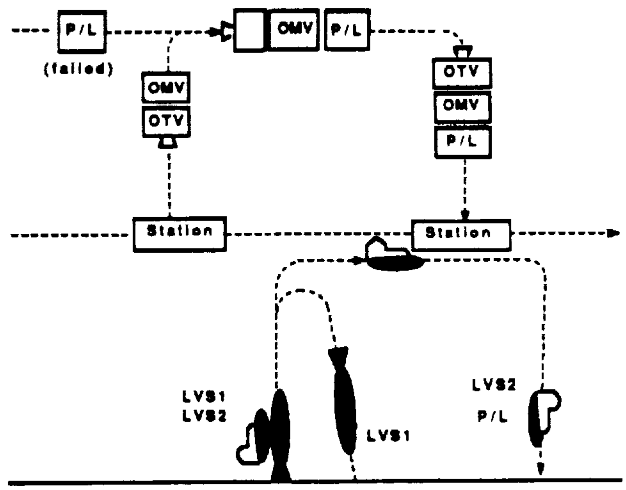


Figure III–6: Transportation Scenario 8: Return to Earth for Repair Using Space-Based Assets

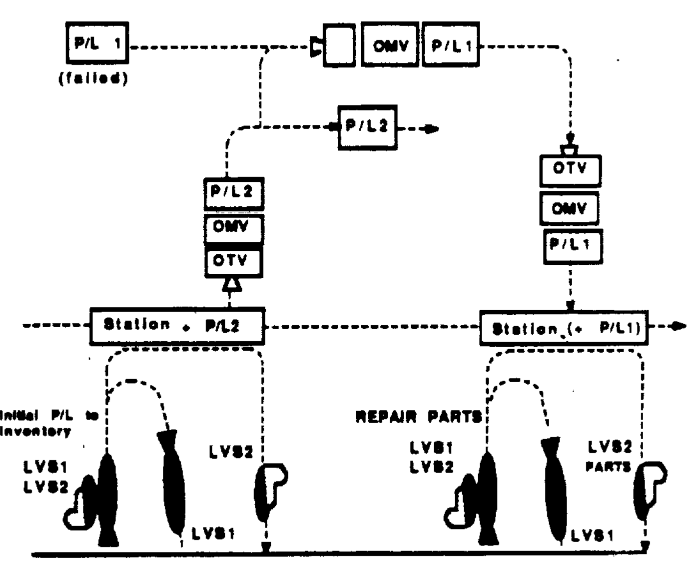


Figure III–7: Transportation Scenario 9: Replace, Return to Station for Repair Using Space-Based Assets

4.1 Transportation Scenario 1

Scenario 1 (Figure III-3) consists of a reusable LV (note that LVS1 may be reusable or expendable) or LV and OTV or expendable LV and OTV for initial P/L placement and/or replacing failed P/Ls. Scenario 1 may be used in conjunction with Scenario 7 for the placement portion of the replace-return-repair mission. If reusable launch vehicles are considered, OTV and P/L checkout failures in LEO may be corrected when and if returned to Earth.

4.2 Transportation Scenario 5

Scenario 5 (Figure III-4) consists of a reusable or expendable LV for transporting P/Ls to the Space Station. The OTV, based at the Space Station, is used to place the P/L into final orbit. The OTV may be reusable or expendable. It is assumed that P/L and OTV checkout failures can be corrected at the Space Station.

4.3 Transportation Scenario 7

Scenario 7 (Figure III-5) consists of a reusable LV, LV and OTV, or expendable LV and OTV for performing on-orbit P/L repair. The OTV and OMV are located at the Space Station. It is assumed that the OMV is capable of docking with specifically configured P/Ls. If repair cannot be accomplished, replacement will be accomplished either via Scenarios 1 or 5 (as specified). It is assumed that OTV checkout failures can be corrected at the Space Station. A repair-kit is delivered from the Earth to the Space Station and, upon mission completion, returned to Earth.

4.4 Transportation Scenario 8

Scenario 8 (Figure III-6) consists of a reusable OTV for acquiring and returning failed P/L to the Space Station. The P/L is then returned to Earth for repair using a reusable LV. It is assumed that the OMV is capable of docking with specifically configured P/Ls. Replacement is performed (prior to returning failed P/L) using an appropriate specified scenario. It is assumed that OTV checkout failures can be corrected at the Space Station.

4.5 Transportation Scenario 9

Scenario 9 (Figure III-7) consists of a reusable LV and OTV transportation system for placing a P/L into orbit and returning a failed P/L in the same OTV flight. A P/L is stored on the Space Station and repair is performed on the Space Station. An initial flight is required to place a P/L into inventory on the Space Station.

5 Baseline Satellite Design

The baseline satellite design used for the cases is the 1995 Ku-band satellite described in Subsection IV-3.2 of Vol. II, Technical Report (NASA CR179527), and summarized in Table III-4. Design features are as follows:

- 3-axis satellite.
- 1,200 kg beginning-of-life mass
- 3,000 W end-of-life power.
- 24 each 50 W Ku-band transponder payload.
- The satellite has a grapple fixture for retrieval by the OMV plus remote manipulator system.

This is a garden variety satellite size and type, appropriate for 1995 launch. A spinner design is not used since it is more difficult to transport (due to thermal problems) and retrieve (due to docking problems). Either the 1995 Ku-band or hybrid satellite could have been selected for analysis, and the retrieval results would not be significantly different. However, a much smaller (and less costly satellite) is expected to have less benefit and a much larger (and more costly) satellite to have more economic benefit from retrieval operations.

Two variations of the baseline design are used: (a) launched from earth to GEO without Space Station; and (b) launched via the Space Station and using the APO scenario described in Subsection VIII-3 of Vol. II, Technical Report (NASA CR 179527). The primary difference is that the baseline (b) has these features:

- 5% less satellite cost.
- Lower tranportation costs (use of OTV).
- Higher reliability (due to operations at the Space Station and use of the OTV).

6 Economic Analysis

Six non-retrieval and retrieval cases, based on the different transportation scenarios, are analyzed using the Model and the relative economic performance is compared. All costs are given in 1985 dollars. The cases are identified by letter as follows:

A. Launch from earth direct to GEO of satellite design (a) using transportation scenario 1. (The Space Station is not used.)

B. Launch from earth to GEO via the Space Station using satellite design (b) and transportation scenario 5

C. Launch to GEO via Space Station (transportation scenario 5). The OTV is used for in-orbit repair missions (transportation scenario 7) as required.

D. Launch to GEO via Space Station (transportation scenario 5). The OTV is used to replace a failed satellite with a new satellite, and a failed satellite is returned to earth for repair (transportation scenario 8).

E. Launch to GEO via Space Station (transportation scenario 5). The OTV is used to replace the failed satellite with new satellite, and the failed satellite is repaired at Space Station and placed in inventory (transportation scenario 9).

F. Launch from earth direct to GEO (transportation scenario 1). The OTV is used for in-orbit repair missions (transportation scenario 7).

This Section is organized by cases as follows:

Manufacturer & model:	RCA Americom, K2
Baseline satellite name:	Satcom K2
EIRP (Conus):	46 dBW
Lifetime:	10 yr
On-board switching:	Among coverage regions
Launch vehicle:	Ariane 4 or STS/PAM D2
Frequency band and bandwidth:	Ku-band, 500 MHz
– receive:	14.0-14.5 GHz
– transmit:	11.7-12.2 GHz
Antenna	
– type:	Offset parabolic, dual gridded
– number:	1
– size:	2.44 m
– mass:	29 kg
– feed array:	2 each 80 elements
– coverage (3 beams):	CONUS and E & W CONUS
– polarization:	H and V, linear
Transponders	
– number:	24
– power:	50 W
– bandwidth:	54 MHz
– TWTA redundancy:	5 for 4
– receiver redundancy:	6 for 3
– mass:	232 kg
– dc power:	2,522 W
Spacecraft	
– type:	3-axis stabilized
– size (bus):	1.57 x 2.18 x 1.77 m
– mass, BOL:	1,200 kg
– power (EOL) at summer solstice:	3,000 W
– primary power:	Solar cells (thin Si)
– batteries:	4 NaS, 150 Ah
– thermal control:	Heat pipes
– attitude and station keeping:	Hydrazine thrusters (ACTS)
– attitude pointing accuracy:	±0.07°
– apogee motor:	Solid propellant

Table III–4: Baseline Satellite Characteristics

1. Baseline Cases (A & B)
2. Repair In Orbit Cases (F & C)
3. Replace, Retrieve, Repair Cases (D & E)
4. Parametric Analysis:
   - Insurance
   - Launch costs
5. Summary of Results

6.1 Baseline Cases (A & B)

The methodology provides for all "new" retrieval – repair cases to be compared with a baseline non-retrieval case in order to accurately assess the difference in economic performance.

Case A, the "business-as-usual" launch from earth to GEO of satellite design (a) using transportation scenario 1, is the baseline for comparison with Case F.

Case B, the launch from earth to GEO via the Space Station using satellite design (b) and transportation scenario 5, is the baseline for comparison with Cases C, D, and E.

6.1.1 Baseline Case Results

Table III-5 summarizes the parameter values input and output by the Model for the two baseline cases A and B. (Only the more significant parameters that change between cases are tabulated; the Domsat III model has many more input parameters as described in Appendix C.) Not only does Case B have a significantly higher expected internal rate-of-return (IRR), but the variation (standard deviation) in the IRR is much less.

Launch costs are based on the Shuttle pricing formula (old cost method). OTV costs assume simultaneous launch of two satellites.

Parameter	Baseline Cases A	Baseline Cases B
P/L Costs: ($M)		
Recurring	48.4	46.4
Non-recurring	24.2	23.2
Launch Costs: ($M)		
Earth-LEO	37.0	17.7
LEO-GEO	9.5	20.9
Reliability: (%)		
Placement	77.3	87.1
Rate of Return (%)		
Expected IRR	9.9	16.3
Standard deviation	4.8	1.7

Table III–5: Baseline Economic Performance

6.1.2 Comparison With C&L Model

The comparison of the DOMSAT III model results with the Financial Model results in Vol. II, Technical Report (NASA CR-179527), is given in Table III-6. The original Financial Model developed by *Coopers & Lybrand* (C&L) gives both IRR (internal rate-of-return) and DTRR (dual terminal rate-of-return), while the DOMSAT Model gives IRR only (but also provides the standard deviation of the IRR).

The "adjusted" C&L Model uses input values that are similar to the DOMSAT Model. The differences between the original and adjusted C&L Model inputs are as follows:

- Effective insurance rates (25% vs. 28.4% for Case A; 12.2% vs. 16.2% for Case B).
- Use of new 1987 tax law.
- Slight change in cost spreading functions.
- Slight change in satellite costs.

Comparing IRRs in Table III-6 shows differences of several points between the original and adjusted C&L Models.

More significant is the lack of agreement between the adjusted C&L Model and the DOMSAT Model. The DOMSAT IRRs are 55% of those for the (adjusted) C&L Model; however, the ratio of ELV to OTV IRR is the same for both models.

There are several reasons for the lower IRRs of the DOMSAT Model:

- The DOMSAT Model explicitly considers failures and accurately figures the IRR

Model (case)	Rate of Return (%)	
	Case A	Case B
C&L Model: (original)		
DTRR	18.8	21.3
IRR	19.9	25.7
C&L Model: (adjust.)		
DTRR	17.7	22.5
IRR	17.3	28.9
DOMSAT III Model:		
IRR	9.9	16.3

Table III-6: Model Comparisons

based on input reliability data. The DOMSAT Model also takes into account the revenue loss from failed transponders during time delays resulting from launch failures. The C&L IRR only applies to successful missions: the IRR for unsuccessful missions is approximately zero after reimbursement of loss by insurance. Thus the IRR is higher for the C&L Model.

- The DOMSAT Model applies the entire net (positive) cash flow to paying off debt. The C&L Model is has a fixed repayment schedule and reinvests any surplus cash. The result is that the DOMSAT Model IRR is lower.

- The DOMSAT Model includes the capital cost of a satellite spare placed in inventory whereas the C&L model does not.

Thus the differences between the two models are, in general, explainable. Each model provides consistent results on a relative basis for all cases considered.

6.2 Repair In Orbit

The two in-orbit repair cases, F and C, are analyzed. When satellites fail, they are repaired in orbit by using the OTV to carry an OMV plus servicer and repair kit to GEO. The repair mission shares OTV costs with another mission to launch a satellite. The repair kit is brought up from earth to the Space Station. An input "repairability" parameter is used to take into account the fact that failed satellites may not be repairable. When satellites fail and are not repairable, new satellites are launched.

An analysis of Cases F and C shows no significant benefit for in-orbit repair. This is due to a combination of high reliability, few incidents of failure that can be successfully repaired in orbit, and the high cost of in-orbit repair.

6.2.1 Case F (Launch Scenarios 1 & 7)

Initial placement of the satellite is based on transportation scenario 1 (Figure III-3), the use of an ELV to place a design (a) satellite in GEO. The OTV is used for an in-orbit repair mission as per transportation scenario 7 (Figure III-5).

Potential things to be repaired, assuming a sophisticated servicer with dexterous hands, include appendage deployment and initial turn on problems with some equipment.

Table III-7 summarizes the case parameters and compares with the baseline Case A. There is a slight improvement in IRR with decrease in standard deviation. The difference is not enough to argue for a change in the business-as-usual Case A. However, the financial risk (standard deviation of the IRR) is reduced and could lead to a preference for Case F.

The non-repair decision factor of 75% reflects the judgement that 75% of the in-orbit failures are judged to be unrepairable in-orbit and therefore no repair mission would be launched. The reliability of repair factor of 87.1% judges that 87% of in-orbit repair missions launched are successful. The overall probability of a failure being successfully repaired is 22%.

6.2.2 Case C (Launch Scenarios 5 & 7)

Initial placement of the satellite is based on transportation scenario 5 (Figure III-4) launch via the Space Station of a design (b) satellite to GEO. The OTV is used for in-orbit repair missions (transportation scenario 7, Figure III-5).

The non-repair decision factor of 90% reflects the statistics that 90% of the in-orbit failures are judged to be unrepairable in-orbit and therefore

Parameter	Case A (Baseline)	Case F (Repair)
P/L Costs: ($M)		
Recurring	48.4	46.4
Non-recurring	24.2	23.2
Launch Costs: ($M)		
Earth-LEO	37.0	37.0
LEO-GEO	9.5	9.5
Repair Mission: ($M)		
Earth-LEO	–	1.3
LEO-GEO	–	30.3
GEO-LEO	–	–
LEO-earth	–	.1
P/L Repair Costs: (%)		
Checkout	–	–
Payload	–	5.0%
Reliability: (%)		
Placement	77.3	77.3
Repair	–	87.1
Non-repairability (%)	–	75.0
Rate of Return (%)		
Expected IRR	9.9	10.2
Standard deviation	4.8	4.1

Table III–7: In-Orbit Repair of ELV Launched Satellite

Parameter	Case B (Baseline)	Case C (Repair)
P/L Costs: ($M)		
Recurring	46.4	46.4
Non-recurring	23.2	23.2
Launch Costs: ($M)		
Earth-LEO	17.7	17.7
LEO-GEO	20.9	20.9
Repair Mission: ($M)		
Earth-LEO	–	1.3
LEO-GEO	–	33.4
GEO-LEO	–	–
LEO-earth	–	.1
P/L Repair Costs: (%)		
Checkout	–	–
Payload	–	13.0%
Reliability: (%)		
Placement	87.1	87.1
Repair	–	74.3
Non-repairability (%)	–	90.0
Rate of Return (%)		
Expected IRR	16.3	15.9
Standard deviation	1.7	1.7

Table III–8: In-Orbit Repair of OTV-launched Satellite

no repair mission would be launched. This factor is high in part because initial launch Scenario 5 uses deployment and checkout at the Space Station to minimize repairable problems.

Table III-8 summarizes Case C which is compared with Case B. A slight decrease in IRR is noted with no change in financial risk (standard deviation of IRR). The difference in IRR is not large enough to argue for a change from the baseline Case B.

6.3 Replace, Retrieve, Repair

Table III-9 summarizes the retrieval and repair Cases D and E and compares them with the baseline Case B. These cases are based upon the use of OTVs based at the Space Station. New satellites are delivered to the Space Station and placed into GEO via the space-based OTVs.

When satellites fail a spare satellite maintained in inventory on the Space Station is placed into GEO and the failed satellite returned via the OTV to the Space Station.

Repair at the Space Station involves taking the satellite into a closed area. Almost anything can be repaired, the same as on earth, with the exception of propellant problems,

No significant change in return-on-investment or financial risk is noted, and there is no compelling argument for the retrieval, repair, and relaunch scenarios.

6.3.1 Return-to-earth Repair (Case D)

Case D returns the failed satellite via the Space Station to the ground for repair and subsequent return to inventory (transportation scenario 8, Figure III-6). There is a low probability of non-repairability (5%) and a high (92.2%) reliability of repair since repair is on earth.

The \$6 M for transportation from LEO to earth is an estimate based upon sharing a cradle used for delivery of a satellite to the Space Station (\$2 M) and NASA fees (\$4 M estimate) for transport of the satellite to earth. (There is at present no Shuttle fee structure for return of items from LEO to earth.)

6.3.2 Repair at Space Station (Case E)

Case E uses transportation scenario 9 (Figure III-7) and repairs the failed satellite on the Space Station. The repaired satellite is then placed into inventory on the Space Station. The probability the satellite cannot be repaired on the Space Station is 30% (considerably higher than the ground repair 5%). When satellite failures are not repairable, new satellites are placed into orbit via the use of the Space Station and the OTV. The reliability of repair is judged to be somewhat lower at 60.3% since the repair is carried out at the Space Station.

6.4 Parametric Analysis

The DOMSAT III Model is used to perform sensitivity analyses for the following cases:

1. Different insurance rates and non-insurance
2. Variation in launch costs

6.4.1 Impact of Insurance

The Model is used to simulate the six cases (A-F) previously analyzed, but utilizing different insurance rates plus the "no insurance" (i.e. self insurance) option.

The insurance multiplier (i.e. multiplier of expected loss) establishes the cost of insurance. For example, a multiplier of 1.25 indicates that the cost of insurance is 1.25 times the expected loss. If the launch reliability is 0.9 and the total loss is \$100 M, then the insurance cost is \$12.5 M. The insurance multiplier is varied from 1.25 to 2.0 for these cases, and 1,000 Monte Carlo simulation runs were made for each case.

The results for the baseline Cases A and B are summarized in Table III-10 and Figure III-8. Table III-10 illustrates the impacts of the insurance alternatives on expected payback period, maximum expected investment, expected net present value, standard deviation of net present value, expected return-on-investment (ROI[1]), and standard deviation of ROI (financial risk). Figure III-8 illustrates the insurance impacts in terms of expected ROI and standard deviation of ROI.

Figure III-9 compares the options of not taking insurance (i.e. self insurance) versus taking insurance (insurance multiplier = 1.25) for the six cases A, B, C, D, E, and F. Not taking insurance increases both the return on investment and financial risk. The range of variation in expected ROI and risk is much larger (for the same range of variation in the insurance multiplier) for Case A than it is for Case B. This is the result of the lower reliability of launch operations with Case A.

It is concluded that the increased reliability associated with operations involving the Space Station have the potential to reduce insurance costs associated with communications satellite business ventures. This potential reduction is based on the assumption that in the long term insurance rates will be related to reliability. The insurance cost for Case A during the 15 year

[1]Note that ROI and IRR are used interchangeably

Parameter	Case B (Baseline)	Case D (Ground repair)	Case E (Space repair)
P/L Costs: ($M)			
Recurring	46.4	46.4	46.4
Non-recurring	23.2	23.2	23.2
Launch Costs: ($M)			
Earth-LEO	17.7	17.7	–
LEO-GEO	20.9	20.9	–
Repair Mission: ($M)			
Earth-LEO	–	–	17.7
LEO-GEO	–	25.2	29.0
GEO-LEO	–	4.4	5.1
LEO-earth	–	6.0	–
P/L Repair Costs: (%)			
Checkout	–	–	2.0
Payload	–	10.0	11.0
Reliability: (%)			
Placement	87.1	87.1	87.1
Repair	–	92.2	60.3
Non-repairability (%)	–	5.0	30.0
Rate of Return (%)			
Expected IRR	16.3	15.6	16.1
Standard deviation	1.7	1.9	1.6

Table III–9: Replacement, Retrieval, and Repair of OTV-Launched Satellite

Performance Measure	Case A Insurance Multiplier 2.0	Case A Insurance Multiplier 1.5	Case A Insurance Multiplier 1.25	Case A No insure	Case B Insurance Multiplier 2.0	Case B Insurance Multiplier 1.5	Case B Insurance Multiplier 1.25	Case B No insure
Expected payback period (yr)	13.4	12.2	11.8	11.6	10.5	10.3	10.2	10.1
Max. expected investment ($M)	476.5	433.0	412.4	388.5	333.1	319.5	312.5	301.8
Net present value, DR=20% ($M)								
Expected NPV ($M)	–167.2	–135.8	–120.9	–99.4	–61.1	–51.1	–46.2	–38.6
Standard deviation NPV ($M)	31.0	28.7	27.7	65.0	22.3	21.6	21.3	36.5
Rate of Return (%)								
Expected IRR	6.3	9.1	9.9	14.4	15.1	15.9	16.3	17.1
Standard deviation	10.6	5.6	4.8	5.0	1.8	1.7	1.7	2.6

Table III–10: Impact of Insurance Rates and the No-Insurance Alternative

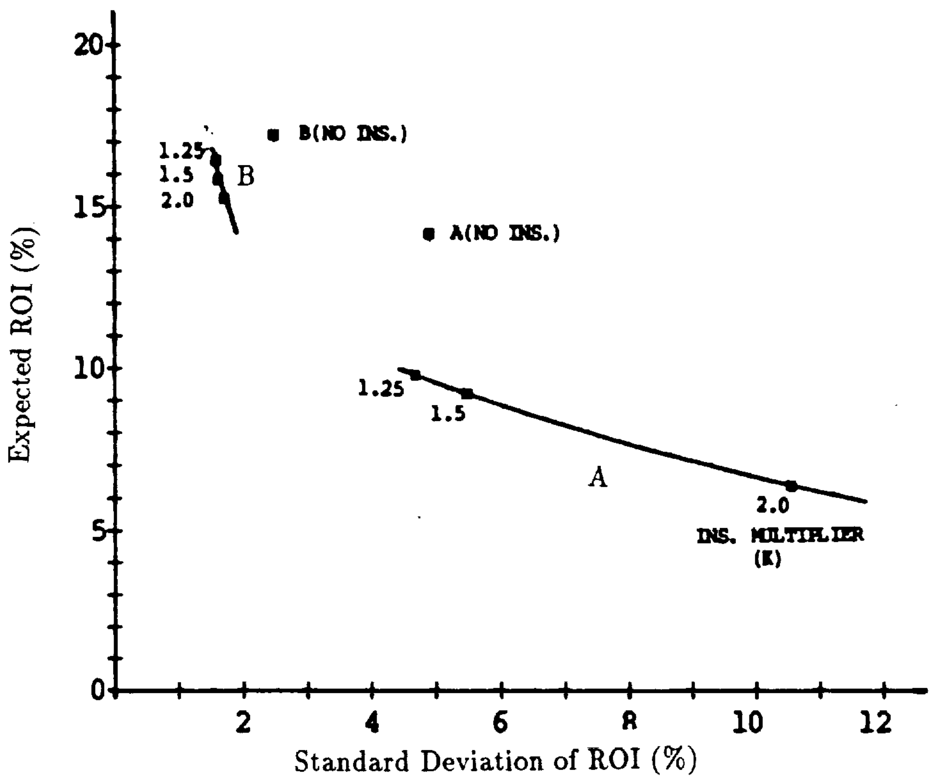


Figure III–8: Effect of Insurance Rate and the No-Insurance Option on Expected Return and Risk

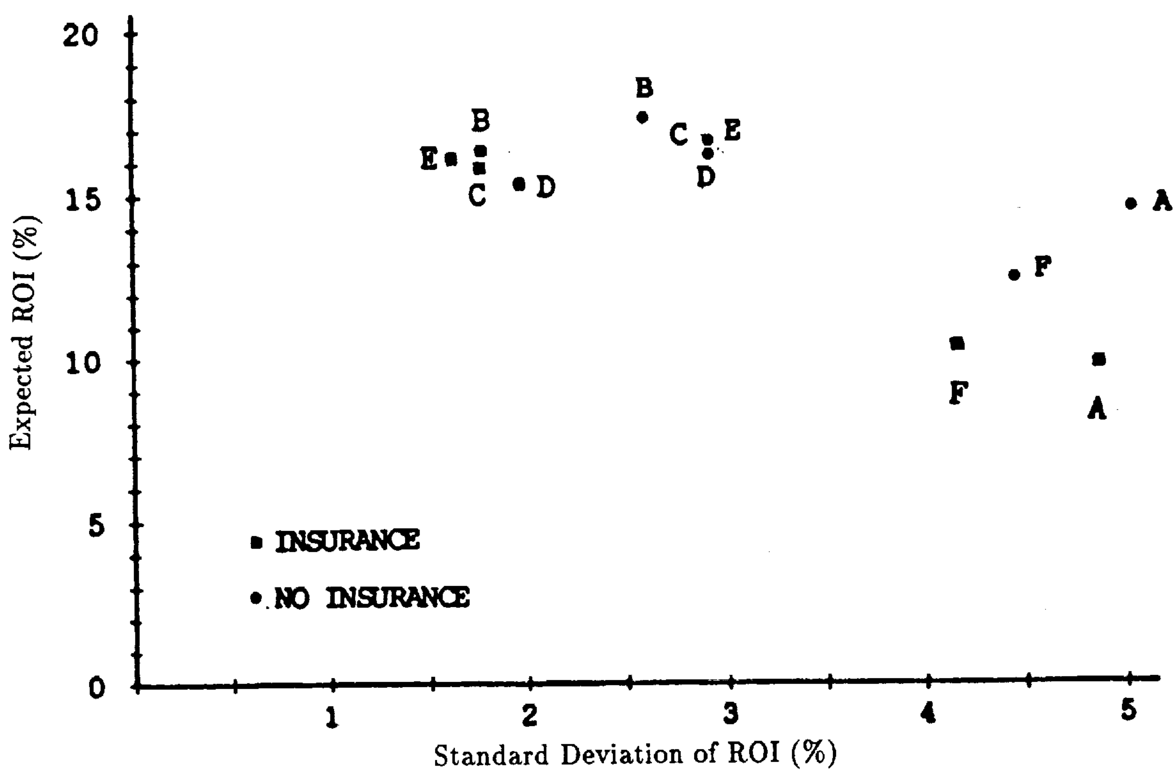


Figure III–9: Comparison Between Taking and Not Taking Insurance (insurance multiplier = 1.25) planning horizon is on the order of \$107 M whereas the cost for Case B is on the order of \$38 M, both with an insurance multiplier of 1.25. The ratio of these costs is approximately 2.8 and remains the same if the insurance multiplier changes.

The question of increased risk perception due to Space Station operations is very subjective. It is likely that insurance companies will be slow to accept the improved reliability and mission mode alternatives created by the Space Station and related operations. Perceptions of increased risk resulting from estimating reliability less than that achieved may result in increased insurance multipliers for certain space operations.

If the insurance multiplier for Case B increased to 1.5 to compensate for increased perceived risk, the insurance cost becomes \$46 M, and the ratio of Case A insurance cost to Case B cost is reduced to approximately 2.3. The impact, of course, would be somewhat less if only insurance increases on certain operations were considered.

6.4.2 Variation in Launch Costs

Cases A, B, E, and F are analyzed to determine the impact of changes in launch costs. Earth to low earth orbit (LEO) costs are varied ±20%, and correspond to the Shuttle or the first stage(s) of an ELV. LEO to GEO costs are varied ±50%, and correspond to the OTV or upper ELV stage(s).

For Cases A, B, E, and F, the following transportation cost change scenarios are compared to the base case:

1. Shuttle (ground to LEO) cost is increased by 20%
2. LEO to GEO cost is increased by 50%
3. Shuttle (ground to LEO) cost is decreased by 20%
4. LEO to GEO cost is decreased by 50%

Table III-11 summarizes the results. The earth-LEO ±20% and LEO-GEO ±50% indicates the transportation costs for the segment are increased or decreased by the indicated percentages. The blanks in the table indicate that the ROI values for these cases are too low to be calculated by the simple algorithm we are using to transform the probability distributions of NPV (at the five different discount rates) into the ROI probability distribution. (This is a programming detail that was not "fixed" since the NPV numbers are calculated and give equivalent information.)

Figures III-10 and III-11 plot the sensitivity of the return-on-investment (ROI) results to changes in earth-LEO (SS) and LEO-GEO (OTV) costs. It is interesting to note the increased sensitivity of the non Space Station cases (A and F) in relation to financial risk.

A more meaningful measure indicating sensitivity is the change in NPV relative to the base cases considered. Table III-12 gives the change in NPV (\$M) for the different launch cost scenarios relative to the standard launch cost case. A sensitivity coefficient can be defined to indicate the change in value (i.e. Δ NPV) that results from a 1 percent change in earth-LEO or LEO-GEO transportation cost. The unit of the coefficient is \$M per percent change.

Table III-13 gives these sensitivity coefficients. Cases A and F are more sensitive to earth-LEO cost changes and Cases B and E are more sensitive to LEO-GEO cost changes.

6.5 Summary of Results

Table III-14 summarizes the input parameters and Table III-15 summarizes the results for Cases A through F. Figure III-12 plots the net present value of the alternatives relative to the assumed discount rate. There is little difference between the baseline Case A and the Case F repair in orbit. Likewise there is little difference between the baseline Case B and the Cases C, D, and E repair scenarios. This is further shown by Table III-16 where the value of all cases considered are shown relative to Case A in terms of incremental net present value. Based on these results, there is no reason to choose a repair scenario over the associated baseline non-repair case.

Case	Expected Payback Period (yr)	Maximum Expected Invest. ($M)	Expected NPV (DR=20%) ($M)	Std. Dev. NPV (DR=20%) ($M)	Expected ROI (%)	Standard Deviation ROI (%)
A:						
Base case	11.8	412.4	–120.9	27.7	9.9	4.8
Earth-LEO, +20%	12.5	443.5	–143.7	27.7	–	–
Earth-LEO, –20%	11.3	381.3	–98.2	27.7	12.4	2.6
LEO-GEO, +50%	12.2	432.6	–135.7	27.7	–	–
LEO-GEO, -50%	11.5	392.7	–106.5	27.7	11.6	3.1
B:						
Base case	10.2	312.5	–46.2	21.3	16.3	1.7
Earth-LEO, +20%	10.4	325.4	–55.7	21.9	15.6	1.8
Earth-LEO, –20%	10.0	299.6	–36.7	20.6	17.1	1.6
LEO-GEO, +50%	10.6	346.8	–71.4	23.1	12.0	2.1
LEO-GEO, -50%	9.7	278.3	–20.9	19.5	18.3	1.5
E:						
Base case	10.2	313.0	–48.0	19.8	16.1	1.6
Earth-LEO, +20%	10.4	326.0	–57.6	20.6	15.4	1.8
Earth-LEO, –20%	10.1	300.1	–38.5	19.1	16.9	1.5
LEO-GEO, +50%	10.7	347.6	–75.1	22.3	13.9	2.2
LEO-GEO, -50%	9.7	278.5	–21.0	17.8	18.3	1.4
F:						
Base case	12.0	414.9	–124.3	28.0	10.2	4.1
Earth-LEO, +20%	13.6	446.1	–147.6	29.8	–	–
Earth-LEO, –20%	11.4	383.7	–101.1	26.3	12.4	2.5
LEO-GEO, +50%	13.2	435.5	–141.4	29.1	6.0	11.5
LEO-GEO, -50%	11.6	394.7	–107.5	27.2	11.9	2.8

Table III–11: Impact of Launch Cost Variations on Cases A, B, E, and F

Launch Segment	Cost Change (%)	Case			
		A	B	E	F
Earth-LEO	+20	–22.8	–10.5	–9.6	–23.2
Earth-LEO	–20	+22.7	+9.5	+9.5	+23.2
LEO-GEO	+50	–14.8	–25.2	–27.1	–17.1
LEO-GEO	–50	+14.4	+25.3	+27.0	+16.8

Table III–12: Change in Net Present Value ($ M) Relative to Standard Launch Costs

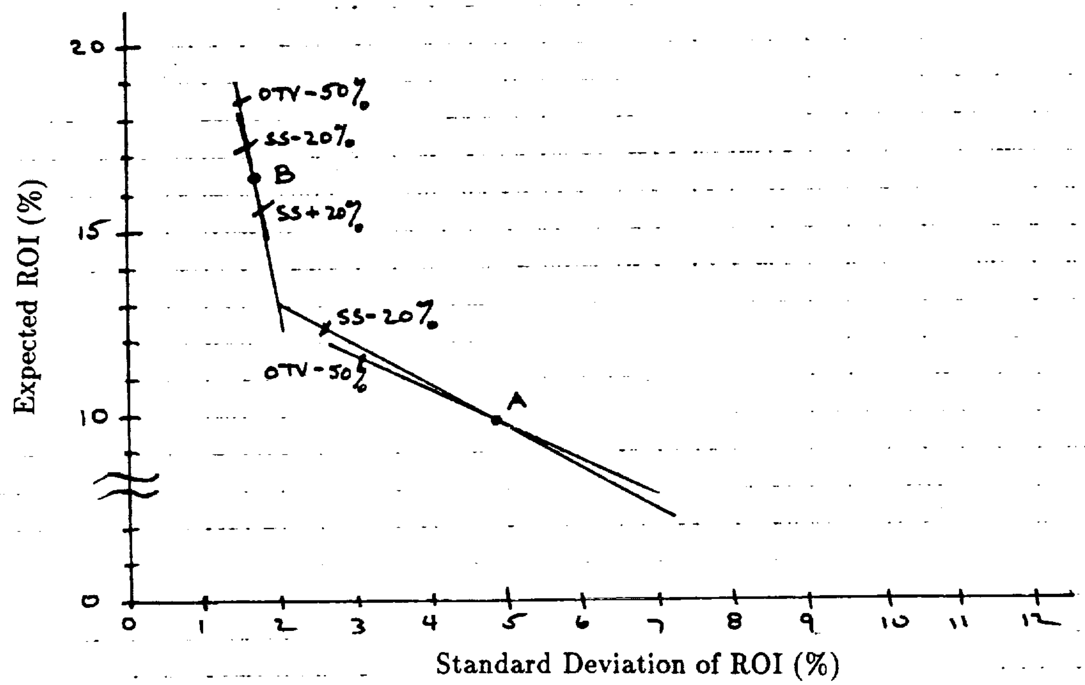


Figure III–10: Sensitivity of ROI to Changes in Launch Costs: Cases A & B

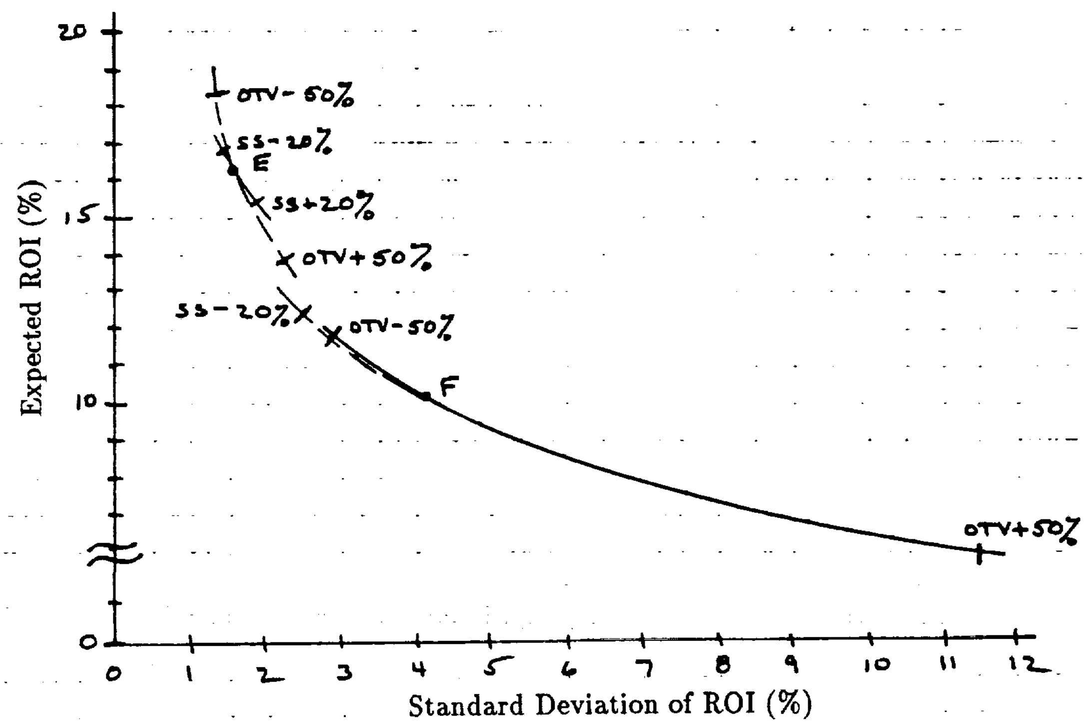


Figure III–11: Sensitivity of ROI to Changes in Launch Costs: Cases E & F

Launch Segment	Case			
	A	B	E	F
Earth-LEO	–1.14	–0.50	–0.48	–1.16
LEO-GEO	–0.29	–0.51	–0.54	–0.34

Table III–13: Sensitivity Coefficients ($M per percent change) for Launch Costs

Parameter	Case					
	A	B	C	D	E	F
P/L Costs: ($M)						
Recurring	48.4	46.4	46.4	46.4	46.4	48.4
Non-recurring	24.2	23.2	23.2	23.2	23.2	24.2
Launch Costs: ($M)						
Earth-LEO	37.0	17.7	17.7	17.7	17.7	37.0
LEO-GEO	9.5	20.9	20.9	20.9	20.9	9.5
Repair Mission: ($M)						
Earth-LEO	–	–	1.3	–	17.7	1.3
LEO-GEO	–	–	33.4	29.6	34.1	30.3
GEO-LEO	–	–	–	–	–	–
LEO-earth	–	–	.1	6.0	–	.1
P/L Repair Costs: (%)						
Checkout	–	–	–	–	2.0	–
Payload	–	–	13.0	10.0	11.0	5.0
Reliability: (%)						
Placement	77.3	87.1	87.1	87.1	87.1	77.3
Repair	–	–	74.3	92.2	60.3	87.1
Non-repairability (%)	–	–	90.0	5.0	30.0	75.0

Table III–14: Summary of Inputs

Performance Measure	Case					
	A	B	C	D	E	F
Expected payback period (yr)	11.8	10.2	10.2	10.3	10.2	12.0
Max. expected investment ($M)	412.4	312.5	315.4	316.6	313.0	414.9
Net present value, DR=20% ($M)						
Expected NPV ($M)	–120.9	–46.2	–52.5	–56.1	–48.0	–124.3
Standard deviation NPV ($M)	27.7	21.3	22.0	24.1	19.8	28.0
Rate of Return (%)						
Expected IRR	9.9	16.3	15.9	15.6	16.1	10.2
Standard deviation	4.8	1.7	1.7	1.9	1.6	4.1

Table III–15: Summary of Results

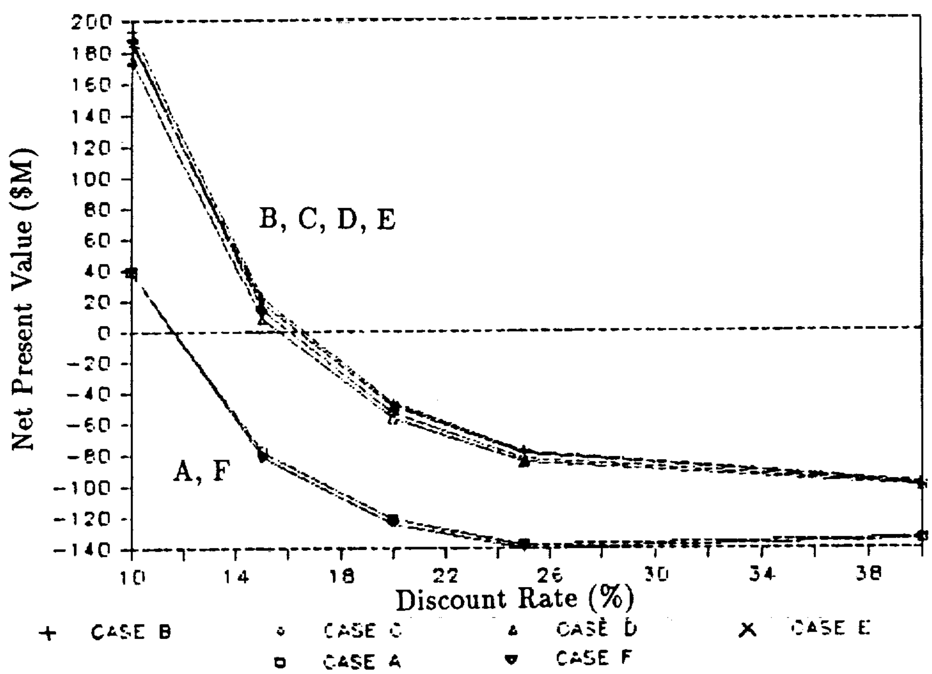


Figure III–12: Expected Net Present Value of Alternatives

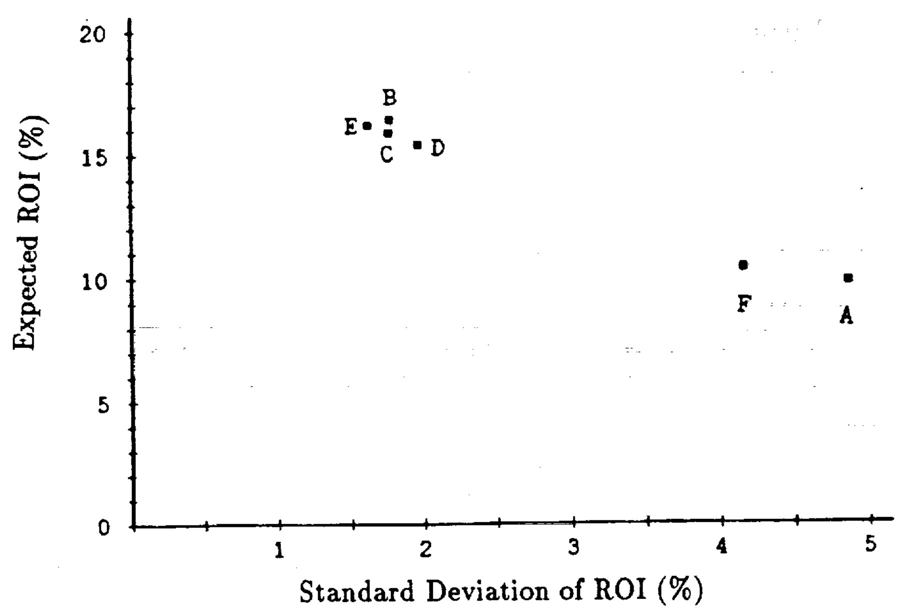


Figure III–13: Comparison of Alternatives – Tradeoff between Expected Rate-of-Return and Risk

	Value of Alternatives Relative to Case A	
Case	Expected Change in NPV ($M)	Std. Dev. of Change in NPV ($M)
A	0	0
B	75	35
C	68	35
D	65	37
E	73	34
F	-3	39

Table III–16: Value of Alternatives Relative to Case A (Comparison at 20% Discount Rate

Figure III-13 compares the alternatives by showing the tradeoff between the expected return-on-investment (ROI) and the financial risk (defined as the standard deviation of the ROI). Again the cases under comparison are heavily clustered, with a significant difference between the expected values and risk of the two baseline cases (A and B). However, it is now seen that repair Case F lowers financial risk by 0.7%, a significant amount. Thus Case F is preferred to Case A.

The large difference between Cases A and B accentuate the results of the initial study – launching a satellite via the Space Station significantly improves expected rate-of-return on investment. Furthermore, it is seen that financial risk is dramatically reduced.

7 Impact on Insurance

An evaluation is given based on the insurance industry interviews of potential on-orbit operations such as assembly of satellites, retrieval of ailing satellites, and repair at the Space Station and relaunch. The discussion is organized into four parts:

1. Potential for Rate Reductions
2. Perceptions of Increased Risk vs. Benefits
3. Requirement for Retrievability
4. Other Issues

Appendix D contains the results of insurance company interviews on which the results of this subsection are based.

7.1 Potential for Rate Reductions

Ultimately, once a data base of experience is built up and past losses are neutralized, insurance rates can be expected to match reliability. Present day reliabilities suggest 20% insurance rates with rates in the low teens foreseen for future launches using the space-based OTV, once reliability has been proved.

A more important point may be the potential increase in insurance capacity as transportation to and from the Space Station becomes insured as "fundamental transport" and not as an exotic spacecraft.

A future satellite launch insurance scenario is likely to be very different from today with a series of tiered rates for different operations:

i. Transport from earth to the Space Station

ii. Assembly, handling operations at the Space Station

iii. Transport by low thrust OTV to final orbit

The insurance industry sees the possibility of the aggregate risk for such a scenario being 10%, accompanied by a significant reduction in the risk of total loss.

7.2 Increased Risk Versus Benefits

The insurance industry likes the idea of passing through the Space Station on the way to GEO for the previously stated reason of risk spreading among component operations. However, the insurance industry has historically been concerned about the introduction of new technologies. The Space Station can temper this concern by utilizing as much proven, existing technology as is consistent with safety, performance, and cost considerations.

One effective method for assuring the satellite insurance industry that the satellite assembly and repair capability is reliable and cost effective is to use it for actual assembly, repair, deployment, and retrieval of uninsured payloads such as future generations of GOES, TDRSS, or other government satellites. Although this approach may appear to be risky for the U. S. Government, it can be considered a key step in the creation of the satellite servicing facility. Once this scenario has been tested and satisfactorily demonstrated, the insurance industry may be willing to provide reduced rates.

Until the assembly and repair of satellites becomes commonplace, customers can expect insurance rates to fluctuate significantly in response to both successes and failures.

It is important to keep the insurance industry involved throughout the long planning stages of this initiative. New issues can then be raised and clarified throughout the entire process. Concurrence from the insurance industry from the outset can help to structure the initiative to avoid insurance problems once the facility is operational.

It will require a major selling job on the part of NASA and the rest of the U.S. government to promote this scenario and convince satellite manufacturers, satellite owners and operators, and the insurance community that on-orbit assembly, repair, and upgrade of satellites is desirable from both a technical and a cost standpoint.

7.3 Requirement for Retrievability

From the insurance company viewpoint, there is no possibility of requiring that all satellites have a retrieval capability. There may be a small incentive in the form of higher rates for those satellites that cannot be retrieved. It is clear that the insurance industry is a follower and not a leader of technology.

7.4 Other Issues

The major other issue we do not address is that of third party liability insurance. This issue is not unique to satellites – it applies to all commercial space activities – and must be addressed by NASA for commercial uses of the Space Station to be viable.

8 Requirements on Station

Physical and operational requirements are imposed on the Space Station by satellite retrieval operations. This subsection catalogs these requirements and recommends to NASA changes required in the Space Station infrastructure necessary to accommodate these operations. The subsection is divided into three parts:

1. Physical requirements
2. Operational requirements
3. Recommendations to NASA

8.1 Physical Requirements

Physical requirements for retrieval and repair operations are the same as those outlined in Section IX of the original study (Vol. II – Technical Report, NASA CR179527, February 1987). The facilities required are summarized as follows:

- Space-based OTV and OMV.
- Storage area for satellites and unassembled modules. Area needs passive thermal control, and micrometeorite and molecular oxygen protection.
- Servicing area for satellites.
- Fueling capability.
- Checkout facilities for satellites.

- MRMS (mobile remote manipulator system) with satellite handling capability.
- "Smart" servicer capable of replacing snap-on modules.
- Multiple mission capability in order to combine missions to GEO.

8.2 Operational Requirements

The following frame of reference is used to develop the operational requirements associated with the assembly, servicing, and repair of communications satellites:

- Satellite construction has changed considerably from current methods and the idea of and techniques for assembling spacecraft on-orbit has been accepted.
- Satellites are transported to the Space Station in separate pieces using either the Space Shuttle or ELVs. The satellite pieces are shipped in some type of cargo container.
- Satellite pieces are assembled and tested using automation and robotics techniques in a working area on the Space Station.
- Once assembled, deployed, and tested, the satellite is transported from the Station to GEO via a low thrust OTV. Once at GEO the satellite would be tested again to insure proper functioning prior to release by the OTV.
- Satellites in need of repair or refurbishment could be retrieved by the OTV from GEO, returned to the Space Station for repair, and then returned to GEO.

Based on this frame of reference, the discussion of operational requirements is divided into four business issues:

1. Control
2. Procedures
3. Liability
4. Costs

8.2.1 Control

The first and perhaps most important issue is who has control of the satellite and its parts at different times and who has final authority for decisions. There are a number of possible answers:

- The satellite owner.
- The satellite manufacturer – who may be different from the owner or who may have control delegated to them by the owner.
- NASA – who may have physical possession of the satellite and who may have the only personnel present during operations.
- An operator of the service facility – who may be the facility owner/operator or a NASA contractor.
- The launch vehicle provider.
- A third party investor or other person with different interests in the satellite.

Clearly, there are a number of possibilities and control may change from time to time as the situation changes. For example, if a condition develops where the satellite threatens the safety of the Space Station, NASA could assume control and take the required action to save the Station.

Of concern to us here is what conditions exist where control is transferred from one entity to another. As can be assumed from some of the examples above, control can be transferred voluntarily such as where an owner may agree to place the equipment under the control of the manufacturer until delivery or, in an extreme emergency, where it can be agreed in advance that control reverts to the party (most likely NASA) required to take action to avoid a disaster.

From a business point of view, owners are unlikely to relinquish control over the asset if there is substantial risk of loss of proprietary data or other information that would result in loss of a competitive advantage or technical lead; situations that could result in significant and costly delays; or their equipment being involved in some activity where it is put into a position of potential loss or damage.

Therefore, with respect to the owner or manufacturer of a satellite, they would desire to maintain control over the equipment at all times during the initial launch, final assembly and testing as well as transportation to a higher orbit. They would be willing to relinquish control under specific circumstances that were clearly defined in a contractual document and followed specific provisions as to circumstances, liability and when control is returned to the owner or manufacturer.

Of all non-technical concerns with regard to operational requirements, the factor of control is most important. The owner or manufacturer will desire to do as much as possible themselves and will view the Space Station as simply a place to do work (much as they viewed the Astrotech satellite processing facility in Florida). They are responsible for the satellite's delivery to the customer in an efficient manner (on time and fully operational) and most likely have severe contractual penalties if they fail to perform. They will be very reluctant to transfer that control to any other party without also transferring the same contractual liability to whomever assumes control.

This issue of control takes on great significance when the entity assuming control is NASA or another government agency. NASA has historically operated on a "best efforts" basis and accepted no penalties for its failure to perform assuming it had made its best effort. While NASA was the only game in town in the launch area, such an arrangement was all that could be gotten, so it was accepted. Now, this is no longer the case and, in particular with regard to encouraging the use of the Space Station servicing capability, may not be adequate to encourage customers to change from ELVs and the traditional construction methods.

NASA must look carefully at any requirement to assume control during an assembly or repair mission, under what conditions that would occur, what guarantees would be made to the customer, and what level of responsibility would be assumed. Obviously, to the degree NASA only provides a place to do work rather than takes charge of the operations, it would be beneficial to the customer from a control point of view if NASA were not involved at all.

8.2.2 Procedures

The procedures issue deals with how various operational requirements are carried out. The satellite industry is quite familiar with the various procedures developed to integrate and launch a satellite on the Shuttle. They will anticipate that similar procedures documents will be prepared for satellite component part transportation to the Station, assembly, test and transport to GEO.

In preparing the new operations procedures NASA should be cognizant of changes needed from previous procedures that were either nonresponsive to user needs or overly biased toward making things simpler for NASA at the expense of user time and resources. While it is not possible to have various satellite manufacturers focus on a future scenario involving Space Station, it is possible to get them to reflect on some of the problems they faced in placing satellite payloads aboard the Shuttle. It is hypothesized that similar issues would be prevalent in dealing with a Space Station system.

The key issues for satellite owners/operators are as follows:

1. Cargo versus transportation
2. Excessive paperwork requirements
3. Control by the owner/operator
4. Scheduling

Procedures to deal with all these issues will have to be developed and put into place. The key appears to be to start thinking about the problems early and work with potential users toward mutually acceptable solutions.

8.2.2.1 Cargo vs. transportation. The first issue concerns the conflict between those persons with responsibility for the cargo and those with the responsibility for the transportation. There will inevitably be issues that arise where needs in one area cause problems for another area. To the degree that components for satellites can be delivered to Space Station as part of a regularly scheduled logistics flight (on either Shuttle or ELV), it may be easier to address some of these problems since the satellite itself will not be a driving factor in the launch schedule.

However, in becoming part of the "regular cargo" on a flight, the satellite manufacturer will have an entirely new set of constraints and activities with which to deal. The key issue in understanding the operational requirements for launch that should be considered by the manufacturer is the packaging of the component parts for assembly on orbit to minimize problems in the payload integration procedures.

8.2.2.2 Excess paper work. The problem with excess paper work appears to be endemic to working with government agencies. Again designing components with flight requirements in mind should help. Also, the ability to separate potentially hazardous material such as fuel and pyrotechnic devices to specific and perhaps bulk shipment flights may help to streamline procedures. Again, having components on standard logistic flights and flights aboard ELVs may also be very beneficial from a paperwork perspective.

8.2.2.3 Control by owner/operator. The control issue was raised and discussed in detail in the previous paragraph and need not be dealt with in detail here. The key issue is the desire by the owner/operator to have access to the equipment at all times.

8.2.2.4 Scheduling. The issue of scheduling is important since time equals money for the satellite owner/operator. Assembly and testing on-orbit means that the question of schedule reliability becomes even more important. Other schedule related issues of importance include the following:

- Will there be adequate storage space for extra components to be taken to orbit and become part of an inventory of parts?
- Once the assembly is initiated, how will robotics or other assembly facilities be scheduled?
- How will test procedures be designed, verified, modified, and conducted in support of the assembly and testing process?
- What happens to the schedule if a part is not available, fails during testing, or needs to be modified or replaced?

8.2.3 Liability

Section III-6 has dealt with the insurance issues associated with the assembly and testing on orbit activity. Suffice it to say that there will be concern in all quarters about who has liability when various activities are being conducted.

However, fear of liability must not become a strangle hold on progress. It is our opinion that the questions of liability that now dominates the space industry is a passing issue that will be resolved in an acceptable manner in the near future. Liability issues will have to be resolved for all Space Station users such as materials science users, earth and ocean observation users, and science users as well as for satellite assembly and testing. The issues are generic and therefore the satellite area will benefit (or suffer) from what ever generic solutions are developed for the problem.

The suggested course of action is to work closely with the insurance industry and various government agencies concerned with this issue to make sure the requirements of the satellite industry receive the attention that is deserved.

8.2.4 Costs

The issues of cost and pricing were also discussed in some detail in Subsection V-5.2. With each operational requirement, it must be considered that there are costs associated with the activity and appropriate pricing policies must be developed. The issue is also somewhat generic and will be addressed for the entire Station. The same recommendation as was made for liability issues above applies here as well.

8.3 Recommendations to NASA

The physical and operational requirements on the Space Station are summarized below along with recommended changes in the Space Station infrastructure to accommodate retrieval and assembly operations.

Physical requirements are as summarized in Subsection III-6.1, and mainly consist of suitable facilities at the Space Station for transport, storage, and simple servicing/repair of satellites.

Transport requirements include the capability of the OMV and/or OTV to retrieve remote satellites, and to combine such missions as launches retrievals, and/or servicing in order to reduce costs.

NASA control of the satellite should be kept to the minimum required by safety and security.

NASA procedures should consider simplicity and cost savings for the user.

Cargo requirements to the Space Station should be integrated with assembly/use requirements on the Station.

Paper work requirements should be minimized.

Scheduling by NASA must recognize that time is money for commercial operations.

Liability insurance issues must be resolved for operations at the Space Station.

A pricing policy for space operations should be developed by NASA that is self-consistent and consistent with long term goals to encourage commercial space operations.

9 Conclusions

The conclusions are based upon a business scenario of a commercial communications satellite with certain characteristics. Results may be different for satellites with significantly different payloads. In particular, inexpensive satellite may be "throw away" designs, while more expensive satellites may be worthly of great effort to retrieve and repair.

The same general point can be made about the cost of space transportation and operations. For example, if space operations are very expensive or unreliable, it will be better to launch another satellite rather than attempt retrieval.

9.1 Use of Space Station

The DOMSAT III financial model analyzed financial performance and confirmed the result of the initial study that there can be a substantial economic benefit to using the Space Station for launch of commercial communications satellites.

The DOMSAT Model explicitly considers failures based on input reliability data and computes return-on-investment as well as financial risk (defined as the standard deviation of the return-on-investment).

Figure III-14 shows the significant difference in performance between the two cases:

A. Business-as-usual satellite launch direct from earth to geosynchronous orbit.

B. Space Station scenario consisting of launch from earth to the Station, operations at the Station, and use of the OTV for transportation from low earth orbit to geosynchronous orbit.

Not only is return-on-investment improved (16.3% vs 9.9%), but also financial risk is reduced (1.7% vs 4.8%) by using Case B, the Space Station launch scenario. To summarize:

Improved return-on-investment occurs by using APOs at the Space Station versus the business-as-usual ELV launch of the satellite. The DOMSAT Model shows significant improvement in rate-of-return (16.3% vs. 9.9%) for the Space Station versus the ELV scenario.

Reduced financial risk is obtained by use of the Space Station launch scenario versus the

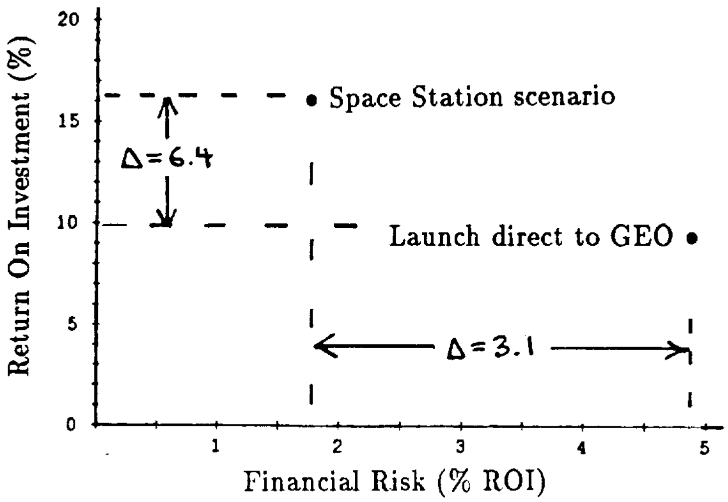


Figure III–14: Improved Financial Performance of Space Station Scenario

business-as-usual ELV launch of the satellite. This is due to the increased reliability of the Space Station and OTV operations versus the business-as-usual launch.

9.2 In-Orbit Repair

Repair scenarios have no significant value for the satellite scenarios analyzed (Tables III-7 and III-8). This is due to a combination of high reliability, few incidents of failure that can be successfully repaired in orbit, and the high cost of space operations.

Our analysis applies to generic communications satellite scenarios and concludes that in general satellites do not benefit from repair-in-space operations. However, it is important to realize that in-orbit repair is highly desirable for selected cases – i.e. for the "easy" cases to reach and/or fix, and for certain high value payloads that may be irreplaceable within the time constraints of their mission.

9.3 Replace, Retrieve, Repair

These repair scenarios also have no value of significance to satellite economics for both ground-based and Station-based repair scenarios (Table III-9). This is due to a combination of few repairable failures and the high cost of space transportation.

Again it must be realized that certain specific mission cases may gain greatly from retrieve, repair, and relaunch operations.

9.4 Impact on Insurance

Insurance reduces risk with a slight reduction in ROI for the Space Station scenarios (Figure III-9). For the less reliable non-Station scenarios, risk remains high with and without insurance – the main impact of insurance is to reduce return-on-investment.

Insurance rate has little effect on ROI for the Space Station scenarios. The insurance rate has a great effect on financial risk for the non-Station scenarios (Figure III-8), with increased insurance rates causing increased risk.

Insurance rates will not decrease until reliability of new operations has been demonstrated.

An increase in insurance capacity is expected as transportation between the earth and Space Station becomes a more routine matter with cargo manifested and satellite components perhaps spread among several loads.

9.5 Impact of Launch Costs

Launch costs directly influence ROI for all cases. The Station scenarios are more sensitive to upper stage (OTV) costs while the non-Station scenarios are more influenced by the initial stage (or Shuttle) launch costs (Table III-13).

Non-Station scenario risk varies rapidly with changes in launch costs (Figures III-10 and III-11).

9.6 Requirements on Space Station

Physical requirements are the same as recommended in the original study technical report. However, the provision for OTV docking with a free satellite undergoing retrieval would greatly increase the flexibility of retrieval operations. This would require a delicate maneuvering capability as well as cold gas thrusters to avoid damage to the satellite.

Operational requirements should emphasize reduction in paper work and the fact that time is money for commercial operations. NASA control of the satellite should be kept to the minimum required by safety and security.

9.7 Follow-On Work

Since the studies to date and resulting conclusions are based upon a specific business scenario and satellite configuration, it is recommended that the robustness of the results and conclusions be established.

1. Additional sensitivity analyses be performed using the current business scenario:
   - Establish the financial impacts of transportation system and satellite reliability and cost.
   - Based upon the sensitivity results, establish within the selected business scenario the conditions that are required for retrieval to be cost effective.
2. Additional business scenarios and satellite configurations be developed and sensitivity analyses performed:
   - Establish the financial impacts of the scenarios, transportation systems, and satellite configurations.
   - Based upon the sensitivity results, establish within the selected business scenarios the conditions that are required for retrieval to be cost effective.
3. Establish the general conditions for which retrieval of communications satellites is cost effective.

Section IV
USE OF EXPENDABLE LAUNCH VEHICLES

This section addresses Task 6, and presents an evaluation of the impacts of Expendable Launch Vehicles (ELVs) on the Activities, Procedures, and Operations (APOs) of the original study Technical Report. The initial report was started before the Challenger disaster and assumed use of the Shuttle for satellite launches. However, recent changes in Shuttle use policy require an evaluation of the use of Expendable Launch Vehicles (ELVs) for transport from earth to the Space Station and to geosynchronous orbit.

The work is divided into five parts:

1. ELV Database
2. Impact of ELVs on APOs
3. ELV Operations
4. ELV Policy
5. Conclusions

1 ELV Database

1.1 Introduction

A database of available and developing expendable launch vehicles is given in Appendix B in order to allow a comparison of ELVs and Shuttle costs and operations. Launch capacity and cost to both LEO and GTO are given in order to allow a comparison for both business-as-usual and APO scenarios. Tables IV-1 and IV-2 summarize existing launch vehicle performance for Low Earth Orbits (LEO) and Geosynchronous Transfer Orbit (GTO).

A cost analysis of various vehicles applicable to this study was made by soliciting cost estimates from the manufacturers. It should be noted that the costs stated in Appendix B are estimates of a business-as-usual launch when a significant operating level has been achieved. Recent launches on different vehicles made by commercial satellites have generally been slightly higher. This is offset by the fact that estimated costs for the Shuttle are also significantly higher than those used in the initial study.

A description of many of the launch vehicles and fairing sizes are given at the end of Appendix B. The size of the vehicle fairing size was not considered as a factor for this study with the exception of the American Rocket Industrial Launch Vehicle (ILV) which is too small for a general launch. The ILV is included in the cost impact and APO sections because it may become a possible vehicle for satellites being launched from the Space Station due to redesign or by launching only part of an assemblable satellite.

1.2 ELV Cost Impact

In order to determine the best launch vehicle for a satellite, the following factors are considered:

- Shape of satellite.
- Volume of satellite.
- Mass of satellite.
- Orbit placement requirements.
- Launch vehicle cost.
- Launch vehicle availability.

This study only examines the maximum payload mass capability and associated cost per kg as parameters to compare with the Shuttle. Of course, the Shuttle has a payload capacity exceeding other launchers as well as other servicing

Company Name	Launch Vehicle	Orbit Description: Altitude (km)	Orbit Description: Inclination (°)	Launch Capacity (kg)	Fairing Size: Dia. (m)	Fairing Size: Length (m)
American Rocket	Industrial L. V.	400	28.5	1,814	2.3	4.6
Arianespace	Ariane 3	200	0	5,800	(14 m^3)	
		800	0	3,450	(14 m^3)	
	Ariane 4	200	0	8,000	3.7	9.6
		800	0	4,500	3.7	9.6
China Great Wall	Long March 2	300	63	1,500	3.1	5.0
Industry Corp.	Long March 3	(Sun synchronous)		3,600	2.7	5.3
	Long March 2-4L	300	28.5	9,000	3.7	10.0
General Dynamics	Atlas G	90	28.5	6,123	2.9	8.4
	Atlas G/LPF	400	28.5	6,577	3.7	9.4
	Atlas H	400	28.5	1,996	?	?
	Atlas E	400	28.5	136	?	?
	ALV	400	28.5	45,360	?	?
Japan	H-2	400	28.5	8,000	3.7	12.0
Martin Marietta	Titan 3	400	28.5	14,061	4.4	12.2
	Titan 4 (Centaur G′)	400	28.5	17,690	4.4	12.2
McDonnell Douglas	Delta 3920	160	28.5	3,452	2.4	?
	Delta 6920	320	28.5	3,787	2.5	4.8
	Delta 7920	320	28.5	4,246	2.5	4.8
	Enhanced Delta 2	320	28.5	4,781	2.8	6.2
		480	28.5	4,536	2.8	6.2
	Delta 2 MLV	400	28.5	5,171	?	?
Proton	D-1, SL-13	400	28.5	20,000	4.2	7.5
Space Services Inc.	Conestoga IV-1	(Sun synchronous)		1,542	1.2	4.6
NASA	Space Shuttle (10/87)	160	28.5	25,700	4.5	10.0
	Space Shuttle (10/87)	400	28.5	13,800	4.5	10.0

Table IV–1: Launch Vehicle Description and Launch Capacities to Low Earth Orbits

Company Name	Launch Vehicle	Orbit Description Altitude (km)	Inclination (°)	Launch Capacity (kg)	Fairing Size Dia. (m)	Length (m)
Arianespace	Ariane 3	GTO	0	1,390	(14 m^3)	
	Ariane 4	GTO	0	4,200	3.7	9.6
		GTO	(28.5 equiv.)	4,720	3.7	9.6
China Great Wall	Long March 2-4L	GTO	28.5	2,930	3.7	10.0
General Dynamics	Atlas G	GTO	28.5	2,360	2.9	8.4
	Atlas G/LPF	GTO	28.5	2,180	3.7	9.4
Japan	H-2	GTO	28.5	2,000	3.7	12.0
Martin Marietta	Titan 3	GTO	28.5	5,670	4.4	12.2
	Titan 4 (Centaur G′)	GTO	28.5	9,072	4.4	12.2
	Titan 4 (dual Star 63F)	GTO	28.5	5,646	4.4	12.2
McDonnell Douglas	Delta 3920	GTO	28.5	1,284	2.4	?
	Delta 6920	GTO	28.5	1,447	2.5	4.8
	Enhanced Delta 2	GTO	28.5	1,819	2.8	6.2
	Delta 2 MLV	GTO	28.5	1,814	?	?
Proton	D-1, SL-13	GTO	28.5	2,000	4.2	7.5
Space Services Inc.	Conestoga IV-1	(Sun synchronous)		544	1.2	4.6

Table IV–2: Launch Vehicle Description and Launch Capacities to Geosynchronous Transfer Orbit

features that allow an electrical system checkout prior to ejection and the capability to abort the launch on orbit if needed. These factors are not considered for this study.

There are two basic classes of ELVs available for launching satellites into Geosynchronous Earth Orbit (GEO):

- Low earth orbit (LEO) launch vehicles; and
- Geosynchronous transfer orbit (GTO) launch vehicles.

The LEO launch vehicles require that the GEO satellite has an additional propulsion system (the upper stage) to perform a perigee maneuver and another propulsion system to perform the apogee maneuver, thus completing the transportation of the satellite from LEO to GEO. The Space Shuttle, Martin Marietta "Titan" series, and the American Rocket "ILV" are all examples of this type. These are also the candidates for launching satellites to the Space Station to enable the APOs described in the initial study Technical Report.

The GTO launch vehicles require only an apogee stage to put the satellite into GEO after separation from the ELV. Examples of this type include the General Dynamics "Atlas" series, McDonnell Douglas "Delta" series, and the Arianespace "Ariane" rockets. Due to its equatorial launch site, the Ariane is launched into an equatorial plane orbit and cannot economically reach the inclined orbit of the Space Station. The other domestic launch vehicles could be modified to deliver a payload near the Space Station.

Figure IV-1 gives a launch cost comparison for ELVs and the Shuttle for optimized delivery to LEO or a Space Station orbit. Cost and capacity values for the ELVs built for GTO delivery are estimated performance and cost values obtained from the ELV manufacturers. It is apparent that the ELVs built for GTO are not as competitive for launching payloads to the Space Station.

An interesting point is the cost/kg of the American Rocket ILV. If its predicted launch costs are valid (the ILV is not yet in operation), the launching of small payloads into LEO may be an option for satellites using the Space Station APOs. The ILV is especially attractive if a large number of launches can be made, possibly bringing the transportation insurance industry into consideration for a larger insurance capability and possibly lower rates.

Figure IV-2 is a plot of the optimum ELV launch cost/kg versus maximum capacity for launches to Geosynchronous Transfer Orbit (GTO). Some examples (Titan, Shuttle) are included with currently available upper stages (Morton Thiokol Star 63F or Centaur G′) to compare the Space Station APO scenarios with business-as-usual scenarios. The cost per kilogram of these examples includes the upper stage cost. It is interesting to note the closeness in cost/kg to GTO for the three major American ELVs – Titan, Delta 2 and Atlas/Centaur. This appears to be a product of the competition among commercial launchers as opposed to the government subsidized launchers such as the Shuttle, Ariane, and Long March. The Conestoga rocket has yet to enter the commercial market and, considering its high launch cost/kg, is not considered useful for further study.

The Ariane rockets have one primary advantage compared with the other GTO launchers. Due to their equatorial launch site, they place payloads in a transfer orbit that is inclined 7° to the equatorial plane as opposed to the 28.5° inclination achieved by launches from Cape Canaveral. This implies that the satellite apogee stage requires approximately 25% less fuel than that of a satellite launched from an American ELV or Shuttle. This fact is taken into account in Figure IV-2.

Tables IV-3 and IV-4 list launch costs for ELVs to LEO and GTO respectively. The price per unit mass to LEO and GTO are optimized costs for each of the vehicles. This cost can be used only for satellites whose mass/volume is optimized for a specific launch vehicle, or a payload that can have additional, usable payload added such as would be possible with an ELV Space Station delivery system. The business-as-usual (BAU) column in Table IV-4 refers to the launch of a 1,176 kg dry mass satellite. Note that the Titan 4 GTO cost includes an upper stage, either one Centaur G′ or two Morton Thiokol Star 63F for an optimal dual launch. The Titan 4 or Shuttle BAU satellite satellite launch uses a PAM D2 or equivalent upper stage which is smaller than the Star 63F or Centaur.

The launch costs in the BAU column of Table IV-4 reflect the fact that most systems are not optimized for weight on the few available ELVs. The Ariane value again reflects a comparable cost for an identical GEO delivery. These costs are used to compare a BAU ELV scenario with the Shuttle BAU and the ELV-delivered Space Station APO scenarios. The BAU scenarios use the 1,176 kg (dry mass) satellite. Only 4 systems – Shuttle, Atlas Centaur, Titan and Ariane – are capable of launching a satellite of this size.

The Ariane can launch the BAU satellite for approximately \$2.3 M less than the Shuttle, and use of the Atlas or Titan increases launch costs by \$8.8 M and \$14.6 M respectively. If these three non-shuttle launch costs are averages, the result is a \$7 M (5%) increase compared to the Shuttle, with a standard deviation of \$8.8 M (6%).

2 Impact of ELVs on APOs

2.1 Introduction

The impact of using ELVs to deliver payloads to the Space Station for APOs is dependent on more factors than simply ELV launch costs. There are other direct costs that will be incurred to interface with the Space Station for man-controlled or automatic rendezvous as well as possible insurance issues. There are also technical issues such as rendezvous, scheduling, and dependence on the Station that must be resolved.

2.2 Rendezvous With Space Station

The only launch vehicle that is currently planned to interface directly with the Space Station is the Space Shuttle. In addition to the Shuttle, the Space Station is equipped with an Orbital Maneuvering Vehicle (OMV) that is used as a "space tug" for external payloads and can operate around the Space Station. There are two pri-

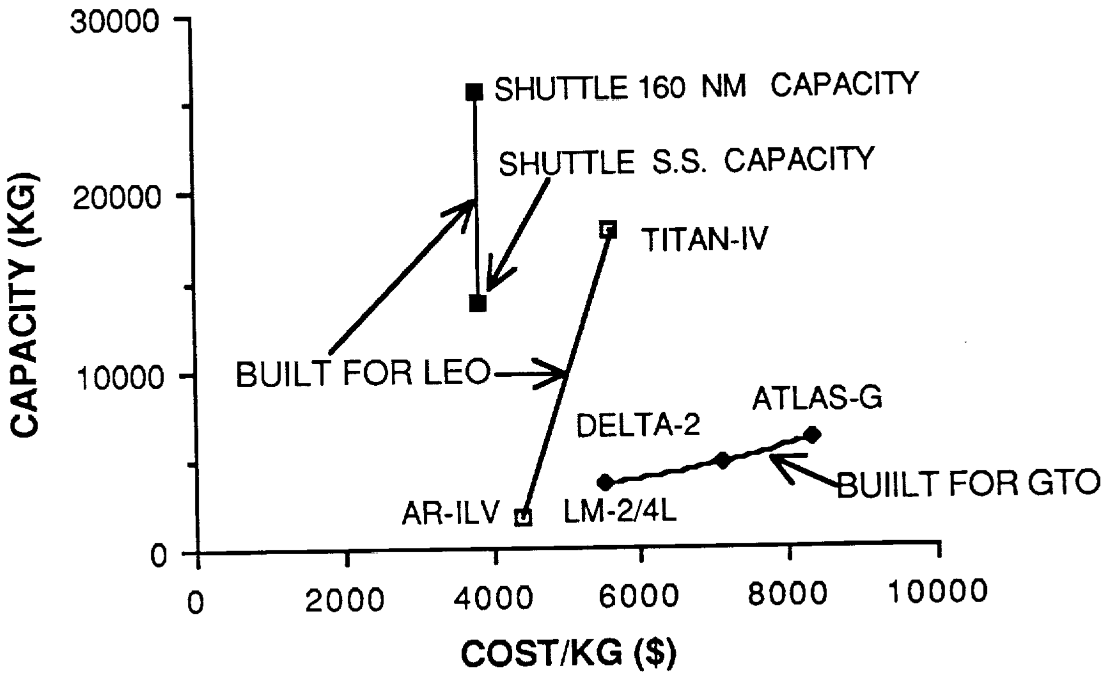


Figure IV–1: Launch Cost Versus Launch Capacity (Low Earth Orbit)

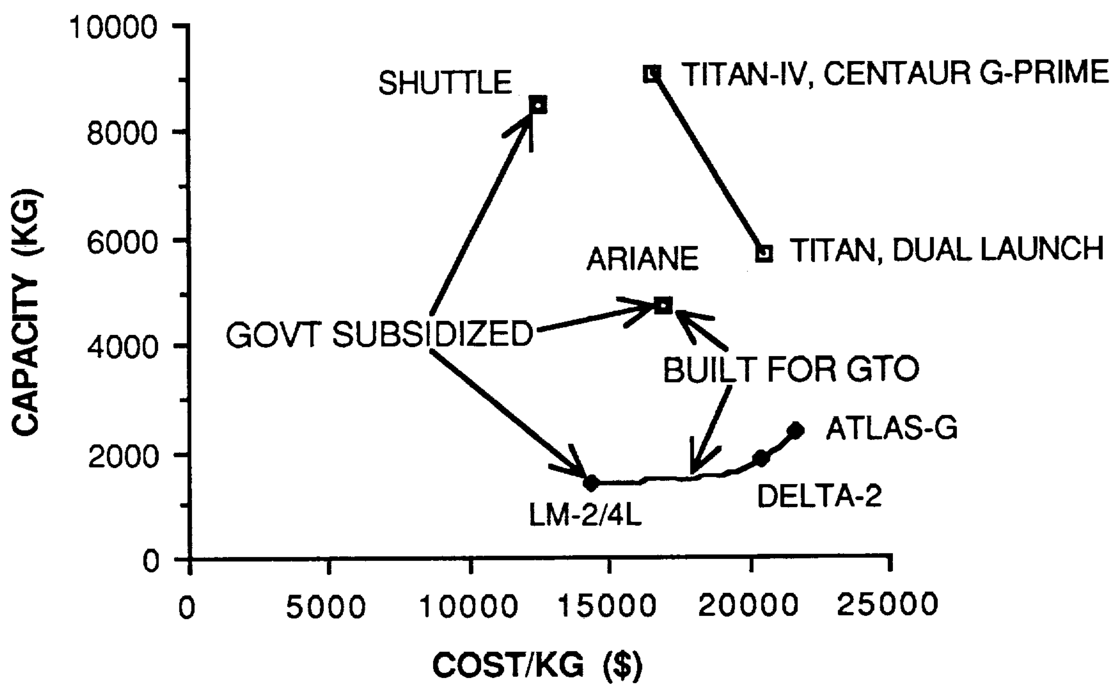


Figure IV–2: Launch Cost Versus Launch Capacity (Geosynchronous Transfer Orbit)

Launch Vehicle	Launch Capacity (kg)	Launch Cost ($/kg)
American Rocket – ILV	1,814	4,400
China Great Wall– Long March 3	3,600	5,500
General Dynamics – Atlas Centaur G	6,123	8,300
Martin Marietta – Titan 4	17,690	5,650
McDonnell Douglas – Delta 2	5,171	7,100
McDonnell Douglas – Delta 6920	3,787	9,700
Space Services – Conestoga	1,542	9,700
Average ELV $/kg	–	7,200
Space Shuttle (dual launch)	25,700	3,850

Table IV–3: Launch Costs to Low Earth Orbit

Launch Vehicle/(Upper Stage)	Base Price ($M)	Launch Capacity (kg)	Launch Costs Per unit Mass ($/kg)	Launch Costs BAU Satellite ($/kg)
Ariane 4, 0° inclination	80	4,200	19,000	–
Ariane 4, 28° equivalent incl.	80	4,200	16,900	17,200
China Great Wall – Long March 3	20	1,400	14,300	–
Gen. Dynamics – Atlas/Centaur G	51	2,360	21,600	22,000
M. M. – Titan 4 (Centaur G′)	100 + 50†	9,072	16,500	–
M. M. – Titan 4 (two Star 63F)	100 + 16†	5,646	20,500	24,500
McDonnell Douglas – Delta 2	37	1,814	20,400	–
McDonnell Douglas – Delta 6920	37	1,447	25,500	–
Space Services – Conestoga	15	544	27,500	–
Average ELV $/kg	–		20,700	21,230
Shuttle with shared launch (PAM D2)	–	13,800	20,200	18,200

† Cost of Centaur G′ or Star 63F upper stage.

Table IV–4: Launch Vehicle Costs to Geosynchronous Transfer Orbit mary reasons for limiting the number and types of vehicles that can operate around the Station:

Safety. The first reason for limiting access is for safety. The safety requirements for the Space Station state that a spacecraft not under human control cannot approach within the designated Space Station safety zone. Control from inside the Station is required for any vehicle to dock with the Station.

Contamination. The second reason is to reduce any contamination and to avoid a build-up of an atmosphere around the Station.

Assuming that the Shuttle is not available for commercial satellite delivery to the Space Station, three options remain:

1. Design an ELV system that can rendezvous with the Space Station and deliver a payload directlyly to it.

2. Use the OMV to rendezvous with the payload in orbit and then deliver it to the Station using the OMV.

3. Do not use the Station (or APOs). Use an ELV to launch directly to orbit.

Option 1 requires that a new navigation, control and guidance system be built into an ELV stage. Such a system would allow close approach to the Station, and then could be controlled from within the Station for the final rendezvous. The safety and contamination issues must be taken into consideration for this rendezvous stage. This would become an added cost for the ELV launch and would most probably exist on only one stage whose design would be funded or at least controlled by NASA.

Option 3, of course, is what we have defined as a business-as-usual satellite launch scenario that is used to compare economic benefits of the APOs.

Option 2 is the most probable method, at least during the early usage of the Station, that ELV payloads will be taken to the Space Station. The use of the OMV creates two cost increases to the original Shuttle supported APOs.

OMV usage fees will be charged to rendezvous, dock, and retrieve the ELV payload.

The interface with the OMV depends on the type of payloads and the type of carrier used for the payloads, and is placed accordingly. The carrier could be the ELV shroud, an enclosed canister that is removed at the Station, a lightweight structure that does not provide physical or thermal protection, or may simply be an attachment point on a satellite that is ejected from the ELV once in orbit.

2.3 APO Cost Impacts

The cost for launching payloads to the Space Station with ELVs built for LEO (AR ILV and Titan IV) shows an average increase (using optimized launches) of $1,175/kg over the Shuttle. This corresponds to a total increase of approximately $1.3 M per satellite. If an estimate of $3 M is adopted for OMV use fees for the payload retrieval, the total increase becomes $4.3 M per satellite. This cost does not include any design or launch costs for an OMV retrievable payload shroud or carrier (perhaps $1 M). This total is less than the average increase in BAU launch costs due to use of ELVs (an increase of $7 M). This shows that the APO values in the initial study report remain valid or could even show a slight increase.

The payload fairing for the Titan IV, which is the only LEO-optimized vehicle large enough for an assembled satellite, would need to be enlarged in order to carry a volume of satellites commensurate with its payload mass. The fairing would probably be equal to the entire upper stage length of the Titan without the Centaur stage. If this is done, 7 or 8 "business-as-usual" satellites could be launched to the vicinity of the Space Station at one time.

This launch scheme would raise the launch costs to approximately $10,600/kg or a net increase of $7.7 M per satellite over the initial APO values. This $0.7 M difference between ELV Space Station delivery and ELV BAU launch is only a small percentage (0.5%) of the total estimated satellite cost and is well within our estimate of the cost "noise". Although this large number of launches is not in agreement with our stated insurance policies, it offers a method to approximate a more conservative costing for non-optimized ELV launches that may occur with new ELVs or with a mixed payload of satellites and Space Station supplies.

There are other indirect cost impacts that may be incurred due to using ELVs. The most noticeable of these is insurance. A slight increase in insurance costs may be incurred by the ELV to OMV to Space Station transfer. This can be offset by a demonstrated safe launch pattern of multiple payloads for assembly at the Space Station. Subsection IV-4, ELV Policy, discusses insurance and other factors.

3 ELV Operations

3.1 Introduction

This subsection gives the normal sequence of events that take place for different business-as-usual ELV missions and the scenario for delivering payloads to the Space Station with ELVs. The actual activities, procedures and operations (APOs) presented in the initial report are not affected beyond the satellite delivery.

3.2 Business-As-Usual Scenario

There are two different types of Business-As-Usual (BAU) scenarios possible with ELVs. The majority of ELVs deliver a satellite (or pair of satellites) to Geosynchronous Transfer Orbit (GTO). The satellite then uses its own systems to transfer into Geosynchronous Earth Orbit (GEO). Some ELVs (Titan 3 and 4) can launch payloads into GTO (using the Centaur stage) or into Low Earth orbit (LEO) where the satellite is responsible for providing its own orbit transfer capabilities.

3.2.1 GTO Delivery Scenario

1. ELV and payload are mated on ground.
2. ELV launched from ground.
3. ELV control into GTO.
4. Satellite deploys from shroud; some appendage deployment may occur. Deployment may include spin-up.
5. Satellite uses an expendable or integral stage (apogee stage) to transfer to GEO.
6. Second satellite deploys from shroud (Ariane only); satellite transfers to GTO.
7. Satellite performs orbit maintenance, deploys remaining appendages.
8. Satellite is tested on-orbit.
9. Satellite begins normal operation.

3.2.2 GTO Delivery Scenario

1. ELV and payload are mated on ground.
2. ELV launched from ground.
3. ELV control into LEO.
4. Satellite deploys from shroud; some appendage deployment may occur. Deployment may include spin-up. If not, satellite will usually spin itself up for perigee maneuver.
5. Satellite uses an expendable (such as PAM or Star) stage to transfer into GTO.
6. Second satellite (if there) is deployed and follows same steps as first satellite.
7. Satellite uses an expendable or integral stage (apogee stage) to transfer to GEO.
8. Satellite performs orbit maintenance, deploys remaining appendages.
9. Satellite is tested on-orbit.
10. Satellite begins normal operation.

3.3 New ELV Scenarios Using APOs

The use of ELVs does not change most of the APOs at the Space Station. The Shuttle APOs, of course, are not performed with the exception of a possible retrieval scenario. Three scenarios are given here that apply to regular use of ELVs.

1. **Retrieval scenarios** could be performed by the Shuttle or by the OMV and Space Station. This scenario is not considered a regular operation but is included because the benefits of performing such a mission, if needed, are large.

2. **ELV LEO delivery scenario** is the expected mission that will allow the Space Station APOs to come into existence with ELV delivery of payloads. This APO involves using BAU ELVs (Titan and American Rocket ILV) to launch into LEO orbit and have their payloads retrieved by the OMV. This is the simplest scenario of the two used for regular delivery to the Station and uses existing or currently developing hardware.

3. **ELV Space Station delivery scenario** requires that the ELV have an additional stage to perform a rendezvous maneuver to the Space Station. Docking can be performed either by this stage or by the MRMS system aboard the Station. This scenario is seen as an advanced procedure for the Space Station. The technology for this type of maneuver is regularly performed by the Soviet space program for their MIR Station. Therefore, because of the possible benefits in time savings for the Station crew, it is recommended that this type of mission be examined in more detail.

3.3.1 Retrieval Scenarios

For this scenario to take place, a failure must occur in LEO within the orbit capability of the Space Shuttle or OMV . This could be a failure in a third stage (either the ELV stage or a separate perigee stage), a failure of a LEO delivery ELV shroud, or other failure that abandons the satellite in LEO. Two different scenarios are possible, one for a Shuttle retrieval and another for an OMV retrieval. The Shuttle retrieval scenario appears to be less practical due to its large mission costs as was apparent in the initial study.

Shuttle Retrieval Scenario

1. Failure of the third stage, the shroud deployment, or another retrievable failure occurs. An emergency retrieval plan commences.

2. Shuttle is launched from Space Station with retrieval kit. Current estimates for retrieval mission readiness is 6+ months.

3. Shuttle rendezvous and grapples "safed" satellite or ELV with RMS or via ELV.

4. Satellite/payload is removed from shroud and/or carrier (if necessary).

5. Satellite is checked out and repaired (if possible and necessary).

6. If an expendable stage is usable, replace into orbit and relaunch.

7. If expendable stage is not usable or satellite is not repaired, dock and secure satellite/payload in cargo bay and return to Earth.

8. Repair/test satellite on ground and relaunch.

OMV Retrieval Scenario

1. Failure of third stage, shroud deployment or other retrievable failure occurs. Emergency retrieval plan commences.

2. OMV is launched from Space Station.

3. OMV rendezvous and docks with "safed" satellite or ELV.

4. OMV returns to Space Station with satellite.

5. Satellite/payload is removed from shroud and/or carrier (if necessary).

6. Satellite is checked out and repaired (if necessary). APO commences if previously planned.

7. If an expendable stage is usable, replace into LEO with OMV and relaunch. If not readily available, store satellite at Space Station.

8. If expendable stage is not available or usable, replace expendable stage (transported from ground to Space Station) or launch with next available OTV or Centaur multiple launch (adapter may be needed from the ground).

3.3.2 ELV LEO Delivery Scenario

This scenario requires that the ELV carrier or satellite be capable of remaining in orbit for an indefinite period of time due to possible problems (scheduling or otherwise) with the OMV or retrieval system. A requirement is also made on the satellite/carrier that it be capable of being safely grappled by the OMV.

1. ELV and payload are mated on ground.
2. ELV launched from ground.
3. ELV control into LEO.
4. Satellite/Payload Carrier are deployed for pick-up (Note that the shroud may be part of the carrier).
5. OMV is launched from Space Station.
6. OMV rendezvous and docks with satellite or carrier.
7. OMV returns to Space Station with payload.
8. OMV is grappled by MRMS or hands off payload to MRMS and waits for its own grappling.
9. Satellite/payload is removed from carrier (if necessary).
10. Satellite/payload is checked out. APO commences as in initial study.

3.3.3 ELV Station Delivery Scenario

This scenario makes less requirements on the carrier and payload (satellite and anything else) that the previous one. A more stringent requirement is made on the ELV system to deliver the payload safely (for the Space Station, its crew, and the payload) and provide a reliable system for docking or being picked up by the MRMS. This poses some unique requirements and benefits that should be examined in a future study. This system makes fewer requirements on the payload which may be beneficial for the overall performance. In addition, this capability would add an automated feature to the Space Station delivery program that would off-load the requirement on the Shuttle system as well as possible providing a lower cost alternative (see Subsection IV-4).

1. Mating on ground of ELV, rendezvous system, and payload.
2. ELV is launched from ground.
3. ELV controlled into LEO.
4. Rendezvous system takes payload from the safe, required ELV delivery distance to the Space Station.
5. Rendezvous system docks with Space Station or safely presents itself for MRMS grappling. This could be done automatically or under Space Station control.
6. Satellite/payload is removed from carrier (if necessary).
7. Satellite/payload is checked out. APO commences as in initial study.
8. Rendezvous system is returned to Earth (via Shuttle) for possible reuse.

4 ELV Policy

This subsection provides some thoughts and ideas on possible policy procedures for ELV use enabling the APOs in conjunction with the Space Station. For example, potential policy issues include:

- Scheduling
- Schedule "bumping"
- Backup scheduling
- ELV availability

The discussion of using ELVs with the Space Station is divided into two topic areas with recommendations made in subsection IV-4.3

1. General ELV Issues
2. Non-Technical Issues
3. Recommendations

4.1 General ELV Policy Issues

The current thinking at NASA has just begun to recognize the potential for using ELVs in conjunction with the Space Station as opposed to using only the Space Shuttle. As yet, there is no clear cut policy for their use.

One of the most serious issues to be faced with regard to ELV usage is control of the vehicle in the proximity of the Station. The current thinking establishes zones of control around the Station which defines areas in which the spacecraft is under earth control, its own control, or the Space Station's control. The issue of control raises significant issues with respect to the level of sophistication or the guidance systems that might be present on an ELV used in conjunction with the Station.

Currently, there are three possible alternatives:

1. The ELV is launched into an orbit near the Station but sufficiently far enough away as to cause no danger. An OMV would be used to rendezvous with the ELV, remove the cargo (satellite, logistics module, component parts, etc) and transport the cargo to the Station.
2. The ELV is launched as in the first option but into an orbit closer to the Station and on-board maneuvering capability be used to bring the ELV payload even closer to the Station where the payload can be reached by the Mobile Servicing Platform and the FTS.
3. The ELV is launched into an orbit near the Station and on-board maneuvering capability be used to automatically bring the payload to the Station and also dock with the Station automatically. This system would be similar to the system used by the Soviets to supply their Mir and other spacecraft.

In each of these options actual control of the ELV would be under the Station control once the payload was in the Space Station's area.

With each of these solutions several issues are raised. The first is the cost and degree of sophistication in the command, control and maneuvering system required to accomplish each of these activities. Clearly, the first option requires the least, the third the most. Discussions with members of the JPL automation and robotics activities indicate that accomplishing the third option is well within the capability of existing technology. However, they suggest that it would be opposed by the U. S. Astronaut office because they want to "fly" all things near the Station as part of the "pilot mentality" that, according to JPL, is unnecessary.

The current option that appears to be most favored is the first. The problems with the second and third options have been addressed and are compounded by fears of potential damage to the Station from an autonomous ELV.

Another issue that has been raised but is often overlooked with regard to ELV payloads, no matter which option is selected, is the issue of disposal of used hardware. The current proposal is to bring back whatever is not used. This option is viable for high cost, reusable systems such as a docking system, but does not show benefit for large carriers which may require special STS cradles, or when ELVs are used as the primary support vehicle. The best option appears to be to equip the ELV and payload with some type of de-orbit retro-rocket sufficient to move it away from the Station and cause orbit deterioration adequate to cause the hardware to burn up in the atmosphere. If this problem is not addressed, there will be such a volume of used carriers and other debris in the area of the Station as to cause a safety hazard to all users.

4.2 Non-Technical Policy Issues

The non-technical operational issues for ELV Use Policy are similar to those addressed for Operational Requirements in Subsection III-6.2. They fall into the same four categories:

1. Control
2. Procedure
3. Liability
4. Costs

This subsection addresses each as a separate issue even though there is clearly significant overlap among them.

4.2.1 Control Policy

As with the actual operations with the satellite or component parts of a satellite once aboard the Station, the owner of the spacecraft will desire to have as much control as possible during the ELV transfer from earth to the Station. However, because of the procedures that have been developed for the traditional launching method, the owner/operator has been conditioned to expect very little actual control over their payload once it is loaded on the launch vehicle. As a result, this may not be as major a problem as it will be later in the process. However, the owner/operator will be very concerned about the frequency and methods by which their satellite or its component.parts are handled once they are on-orbit. This will raise major issues with regard to both control and, as will be discussed below, liability.

4.2.2 Procedure Policy

As with current launch operations and as was discussed for operations on the Station (Subsection III-6.2.2), detailed procedures as to how various activities associated with the ELV movement of the payload to the Station will have to be developed. As was noted above, the major area of concern will be the amount and type of handling that will have to be done in moving the spacecraft or components from the ground to the Station. For this reason Option 3, which results in minimal handling and relies on proven automated systems, is preferable.

A potential benefit here is the design and development of standard carriers, logistics modules or combinations thereof for use as major component protection as well as transport mechanisms. The design of such hardware would facilitate the use of robotic handling of the satellite, components and other cargo. It would also reduce the potential for damage with subsequent liability issues as will be discussed below. Of key concern, which will also be discussed below, would be the cost of such a carrier. It would be desirable that the carrier be reusable, however, there is the problem of returning it to earth. It would have to be designed for return by the Shuttle or as part of some type of return capsule.

As with the operations on the Station, the development of procedures covering all aspects of delivering ELV launched payloads to the Station is essential. NASA has just finished a transportation study with respect to Space Station. However, this study will not be made public for some time because it was considered incomplete in its present form. A second study, "ELV Assessment for Space Station Logistics", by Robert R. Corban of NASA/LeRC also addresses these issues.

It is known that NASA is actively considering the use of ELV in conjunction with Station. As a result, procedures for Station bulk cargo and logistics resupply by ELV will certainly be developed. Owners - operators considering using the Space Station for satellites should insure that procedures are developed to accommodate their needs.

The question facing those considering use of the Station for satellite assembly and preparation for placement in GEO is whether to take the satellite or components to the Station on a dedicated ELV or as a portion of the cargo on a general logistics flight. The advantages of a dedicated flight are increased control but there is no spreading of the insurance risk and there may be a substantial cost penalty. The advantages of going on a regular logistic flight are the opposite.

4.2.3 Liability Policy

The major liability issue facing the use of ELVs is with respect to the Station itself. Clearly, there is inadequate insurance or any other means to protect any ELV operator against significant damage caused by an ELV to the Station – the costs involved are simply too high. This is the major reason behind the desire to keep ELVs away from the Station and use an OMV to move items in close proximity to the Station. This major question of liability will have to be resolved before any ELV operations can be conducted. However, this question is not unique to the satellite industry and will probably be resolved early in the Space Station's history when ELV launched logistics flights are initiated. The satellite industry will most likely follow whatever procedures are adopted.

The second liability issue is between the satellite or satellite components and other cargo that may be present on the same ELV flight. This is the question of potential damage caused during the handling and movement of components by robotics or by astronauts. Much can be done to minimize this risk by developing and using carriers as discussed above and in preparing detailed procedures. It is most likely that some type of insurance protection will be available for these activities.

4.2.4 Cost Policy

The basic premise used in the initial study is that satellite owners and operators will not use the Station unless it is either less expensive than going directly to GEO or significant increases in capability can be gained. Therefore, in determining actual costs of placing a satellite in orbit by ELV with a stop at the Station, a number of cost components must be considered:

- Pre-launch preparation
- ELV launch cost to Station
- Costs of carriers or other handling equipment
- OMV costs versus on-board maneuvering/control capability
- Costs of assembly, testing and other services provided on the Station
- Transport to GEO by OTV

Many of these costs have been discussed in other responses to various tasks in this report. For the purpose of this task we will concentrate on only the ELV launch costs to Station, costs of carriers or other handling requirement, and costs of OMV or on-board maneuvering/control capabilities.

The costs of ELV launch are to a large degree a function of what portion of the ELV is used for the satellite or components. With the advent of the Station, it is likely that existing ELVs that are now optimized for GEO launch will be redesigned for use with Station. In addition, smaller vehicles such as American Rocket's Industrial Launch Vehicle and larger vehicles such as the ALS or Shuttle C will become available for use with Station. As was discussed above, to the degree that satellites or components can become cargo along with other items going to the Station, the costs should be impacted in a favorable way. Shipping components for assembly on orbit rather than assembled satellites will also benefit cost in that they can be fit into cargo areas as regular rather than dedicated cargo requiring lower cost handling. The insurance benefit of spreading the costs is discussed in Appendix D.

The key to reducing cost for ELV transport of satellites to Station is in making them as much like normal cargo as possible. However, as was discussed above, moving in that direction reduces the satellite owner/operator's control and reduces his priority for activity. Since this will be a major change from the way satellite owner/operators are currently treated, this may require a major adjustment on their part.

A major issue is the cost of the various carriers that will have to be used to transport logistics and other material to the Station. Such carriers will be developed as part of the basic Space

Station budget process for use by both Shuttle and ELVs. It is very important that the needs and requirements of the communications satellite industry be made known in the early stages of carrier development. This would allow carriers capable of transporting satellites or their components to be manufactured as a standard Space Station logistics component rather than as a specialty item later in the process and at a much higher cost.

Since carrier requirements and designs are as yet vague, the Ford Aerospace study might be of significant benefit to NASA in suggesting requirements and possible design features for a carrier compatible with satellite industry needs as part of this effort.

Current NASA plans do not call for the return of logistics elements launched on an ELV except during the assembly phase of Station. This single event creates special needs that must be met by the ELV and Space Station manufacturers. Two possible solutions result: (1) make the carrier as cheaply as possible to withstand only one use (perhaps inflatable parts such as the inflatable antennas currently being examined), and (2) devise a carrier that can be returned by Shuttle (perhaps with partial disassembly so that it requires less volume). These present unique design challenges for engineers but the key issue is to insure that price considerations are very high on the list of design parameters.

A similar issue exists with respect to the tradeoffs between use of an OMV and placing guidance and control capability aboard the carrier. Clearly the OMV is being developed from NASA funds and as a result would not become an expense directly attributable to the needs of satellite users. However, as currently envisaged, the OMV will be very expensive and use of it will almost certainly also be expensive due to the need for astronaut guidance and operation. NASA should consider the impact of costly OMV use on the possible appeal of Station to satellite owners/operators.

5 Conclusions

5.1 Summary of Results

Cost analysis shows that using ELVs in place of the Shuttle changes launch costs, but does not change the value of the APOs when comparing business-as-usual ELV delivery with ELV Space Station delivery.

There are also benefits which could be gained that may enhance the APO values. Launching multiple support vehicles on a regular basis offers the satellite industry with a method of spreading the launch risk over several launches and assembling the satellite at the Space Station (see Section V). This may eventually drive insurance costs down, increasing the values of the assembly APOs.

The usefulness of ELVs to support a Space Station can be seen logically, but can also be seen by example from the Soviet space program. The MIR station is supported by a system similar to the one presented here. Logic also dictates that the Station not be totally dependent on the Shuttle over its entire life. The system presented above is only one example that could be used as a guide for providing a solution to the unresolved issues.

Significant effort beyond the ideas suggested in this section and entire task should be devoted to working in the areas of both ELV support and automatic docking systems. These areas will prove to be a key to the future of the Space Station operation and a focus of reducing the costs of space utilization and exploration.

5.2 Recommendations

There are a number of unresolved policy, cost and technical issues that deal with using ELVs to support the Space Station. These issues apply to commercial, government, and military satellites.

5.2.1 Need for ELVs

Several reports show the need for Space Station support will most probably not be met by the STS alone. In addition, various studies show the stated NASA and military (not including SDI) needs for the Shuttle and domestic ELVs in the near future (up to the year 2000) outweighs the current capability of STS and ELVs combined. This assumes that no commercial needs for launch vehicles exist and a reasonable percentage of slated projects are followed through.

The conclusion is that an ELV system will most likely be needed to support the Space Station. However, any additional work load on the Space Station crew will have major impacts on the Station productivity. It is the recommendation of this study that an additional set of studies be developed and followed through by NASA, or that existing studies be given specific scope to examine the use of a specialized ELV Space Station support system. The basic outline of such a system has been developed as an ideal system that can be met with today's technology and with a cost impact that can be minimized through repeated use and commercial operation. This system addresses and attempts to solve many of the issues that have been pointed out.

5.2.2 Proposed ELV System

The system we have developed consists of a mid-sized ELV system that would deliver a payload carrier of sufficient size to fit two common-sized satellites without upper stages (fairing approximately 4.4 m by 7.6 m. This system could be derived from an existing ELV design to defray design costs. A reusable guidance, navigation and docking system would be attached to several pre-designed carriers. This system would probably use a dual propellant system, a mono or dual propellant system to deliver the payload from a safe ELV launch distance to the Station area, and a cold gas system to provide the final maneuvering and docking within the Space Station safety envelope.

The maneuvering and docking system should be designed to be a man-rated safe system that can perform all its functions automatically. A Space Station override should be included as an added safety feature. The maneuvering and docking system would be removed at the Station with the exception of a small, low-cost, disposable system that would take the carrier and any Space Station waste into an orbit where it could enter and burn in the atmosphere. This system would most likely be spin stabilized prior to ejecting from the Station (spin table fixed on Station), and would consist primarily of a timer or remote operating system and a small solid rocket that would supply the needed velocity change. The higher-cost, maneuvering and docking system can be returned on the Space Shuttle with other Space Station items.

This is a system that can be proven early and can solve issues dealing with liability because the ELV system could be controlled by NASA (being a single system) and eliminate the multiple transfers that would be required with an OMV scenario. The use of ELVs would provide NASA with a system that can easily accommodate small schedule upsets because no turnaround is needed (by having several maneuvering and docking systems in use).

The use of such a system can provide almost unlimited Station support, does not put a high load on the crew, and provides a regular waste disposal system for the Station, opening up additional STS return capability for the ELV docking and maneuvering system and other returnable items. Payloads, as well as hard and soft resupplies can be delivered to the Station on a regular basis as well as allowing short term, high frequency supports (many payloads over a few days) that could prepare the Station for a long duration confinement period for long lasting low-g experiments.

The launch capability of the Shuttle can then be dedicated to crew changes and large payloads which are more infrequent, reducing the launch load on the Shuttle fleet, extending the life of each vehicle, and providing a system that is not dependent on only one launch system that could be grounded due to a failure or long, unexpected launch delays.

Section V

ON-ORBIT ASSEMBLY AND SERVICING

1 Introduction

This section presents the results of Task 7, On-orbit Assembly and Servicing. Designs are developed for serviceable satellites, assembly and launch scenarios are hypothesized, and satellite economic performance is compared with a conventional baseline system. The work is organized in eight subsections:

1. Introduction
2. Modular Satellite Designs
3. Assembly and Launch Operations
4. Servicing Scenarios
5. Economic Performance
6. Requirements on Station
7. NASA Course of Action
8. Conclusions

The basis for this task is that the Space Station can serve as a low earth orbit base for satellite servicing, assembly, and launch operations. The satellite can be assembled and tested at the Station before being transported to its final destination via low thrust space-based OTV, thus reducing the risk of beginning-of-life failures. As the satellite reaches its end of life, a remote servicer is sent to exchange failed or degraded components and replenish consumables, thus extending the life of the satellite. The net result of such a scenario is to reduce program costs through reduced insurance, launch, and replacement costs.

This section develops the designs for serviceable spacecraft, gives assembly and launch scenarios, and compares economic performance against a baseline business-as-usual scenario. Before the results on modular satellite designs are presented, three topics are discussed as background:

i. **NASA Infrastructure** details the assumed Space Station infrastructure required for assembly and servicing of modular satellites.

ii. **Baseline Satellite Design** gives the non-modular design against which the economic performance of the modular design is compared.

iii. **Serviceable Components** of a satellite are identified.

1.1 NASA Infrastructure

In order to perform assembly and servicing activities either at the Space Station or on-orbit, the following infrastructure is assumed to exist:

- Full operation capability Space Station:
  - Orbital Maneuvering Vehicle (OMV)
  - Orbital Transfer Vehicle (OTV)
  - Payload integration and checkout facility
- Remote satellite servicer system (available by late 1990s to early 2000s)
- Fluid transfer via a refueling kit

Transportation of the satellite servicer, OMV, refueling kit, and the satellite replacement parts from the Station to GEO is via the OTV.

1.1.1 Transportation Systems

Orbital Transfer Vehicle

The Orbital Transfer Vehicle (OTV) is a reusable cryogenic upper stage that has a throttleable engine for high and low thrust maneuvering capabilities. It uses aerobraking for descending to lower orbits, thus substantially reducing fuel consumption.

The OTV is used to perform the large orbit change maneuvers necessary to transport the servicing equipment, spares, and OMV to GEO and to return the servicing equipment and debris to the Station.

Orbital Maneuvering Vehicle

The Orbital Maneuvering Vehicle (OMV) is used to provide fine maneuvering control during proximity and rendezvous operations. It has three separate propulsion systems:

i. a bipropellant system for large delta velocity capability,

ii. a monopropellant system for moderate delta velocity capability, and

iii. a cold gas system for fine control and contamination prevention.

The OMV has a radar system for locating remote targets for rendezvous and TV cameras for object location and docking, and can operate autonomously or can be controlled by a pilot on the ground. It will be designed to interface with the remote servicer and provide power and communications support to the servicer and attached payloads.

The OMV also has a "contingency hold" capability which could allow it to remain in geosynchronous orbit for up to nine months. Thus the OMV could perform additional servicing missions without having to return to the Station for servicing, thus reducing the mission transportation costs. However, use of contingency hold implies production of at least two OMVs in order to minimize the impact on other operations at the Station.

1.1.2 Remote Servicing Systems

The servicer could be robotic or telerobotic with one or more arms and is transported by the OMV along with the Orbital Replacement Units (ORUs). There are two current approaches to the servicer design.

1. The **Integrated Orbital Servicing System** (IOSS) applies existing industrial robotic technology to satellite servicing, and carrys out a preprogrammed set of instructions to exchange modules, connect umbilicals, and perform other servicing tasks.

2. The **Flight Telerobotic Servicer** (FTS) is a proposed telerobotic system for the Space Station that can be mounted on the OMV for remote servicing. It uses technology similar to that developed for nuclear teleoperator systems and may have two or more dexterous arms, advanced sensory capabilities and should be roughly equivalent to a suited astronaut.

1.1.2.1 IOSS. The Integrated Orbital Servicing System was developed by NASA, Marshall Space Flight Center (MSFC), and is based on proven industrial robot technology. Figure V–1 shows a 1 G engineering test unit built by Martin Marietta which has been used in many successful demonstrations of module exchanges. It has a six degree-of-freedom arm driven by complementary ground and space-based computers, and a standard end effector for module exchanges. It can accommodate other end effectors and tools to accomplish a wide variety of tasks.

The IOSS carries out a preprogrammed set of instructions under ground operator supervision. Since this system follows a programmed set of motions for each servicing operation, it assumes that all geometries are known in advance and do not vary over time. Thus the locations of the modules, fuel ports, OMV docking points, and any obstacles must be known well in advance in order to be programmed.

The OMV docking operation will initially be performed manually by a ground operator utilizing visual references for alignment and thus

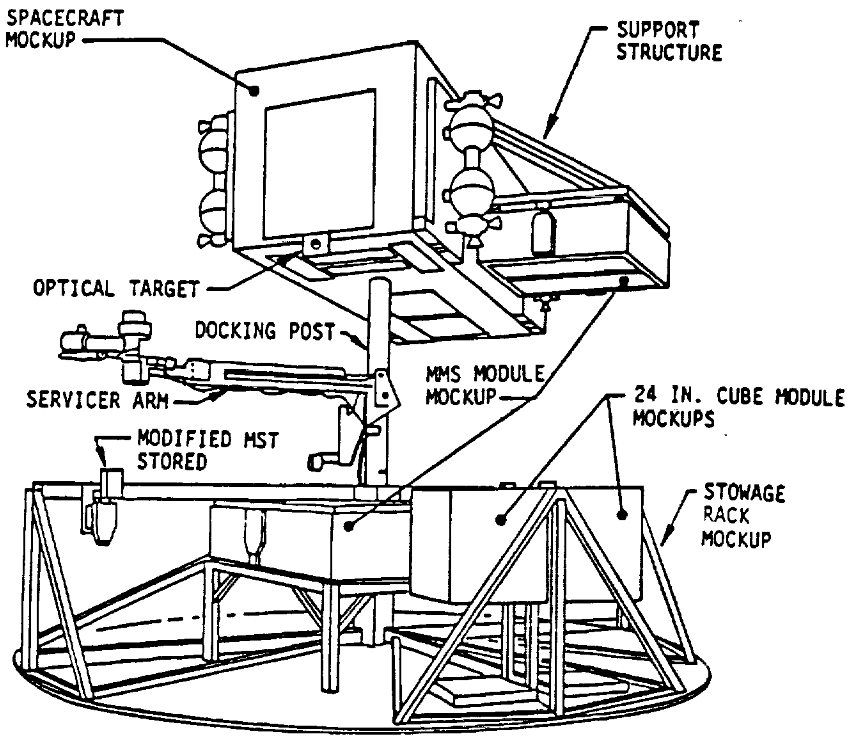


Figure V–1: Integrated Orbital Servicing System: Configured for Demonstration

allows for operator induced errors. However, a possible difficulty with the IOSS system lies in docking misalignments. Any error in docking geometry induces a constant error in each servicing operation as the IOSS programming is based on assumed geometries between the satellite and the OMV. The most likely docking misalignment is around the roll axis since the OMV docking interface is rigid in two dimensions. The current OMV docking interface is based on the RMS end effector design. This device rigidly aligns itself in pitch and yaw but allows a roll misalignment. One possible solution is to change to a different docking adapter which self aligns and becomes rigid in all three dimensions after docking. Other possible solutions involve measuring the roll error and having the software update the arm trajectories accordingly, or to use sensors to close inner control loops to actively control the end point of the end effector.

The IOSS is capable of three modes of operation:

i. Supervisory. The servicer carries out a preprogrammed set of tasks under the supervision of a ground operator. The operator observes the servicer's operation via a camera mounted above the end effector and may interrupt the operation at any time.

ii. Manual Augmented. The operator controls the arm via a hand controller.

iii. Manual Direct. The operator commands the individual joints via a switch panel.

The two manual modes provide the flexibility for the operator to interrupt an operation and perform manual corrections in real time. This capability gives the IOSS the flexibility to handle unplanned events or perform additional repairs during servicing operations.

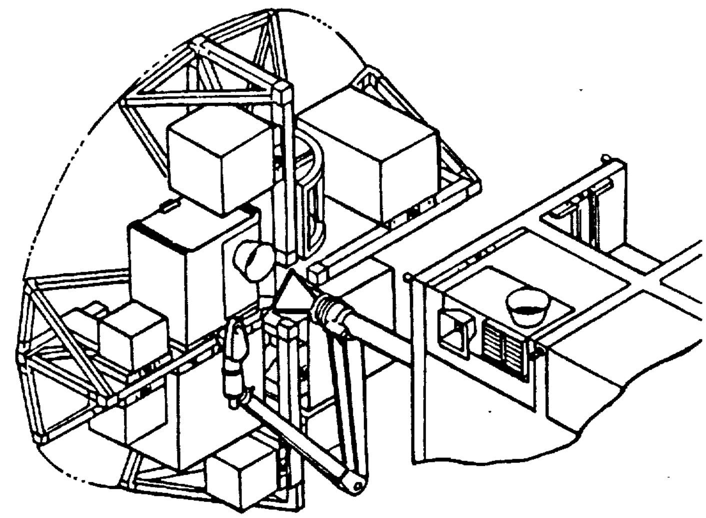
The basic module exchange operation for the IOSS consists of removing the old module from the spacecraft interface; flipping it over for loading into the ORU rack; inserting it into a vacant location on the ORU rack; removing the replacement module from the ORU rack; flipping it over to insert in the proper location on the spacecraft and inserting it into the spacecraft interface mechanism (Figure V–2).

The refueling operation consists of removing the refueling umbilical from the storage rack and inserting the fluid coupling into the fueling port. The fluid transfer is performed by the refueling kit. Once the fuel transfer has been completed the arm removes the coupling from the port and returns it to its storage location.

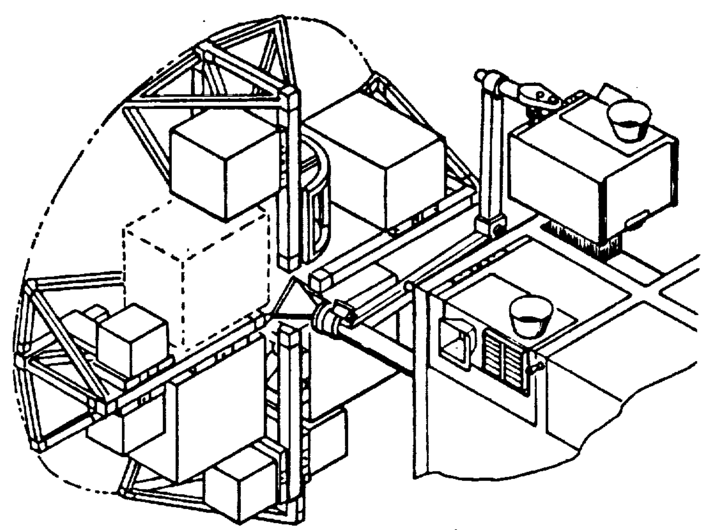
The IOSS is a simple design that can perform a wide range of servicing tasks such as inspection, module replacement and refueling. This servicing system requires that the satellite has a modular design but allows the designer complete flexibility in designing the individual modules. The only requirement is that the satellite module interface be compatible with the IOSS end effector. The IOSS, however, can accept special end effectors or tools which gives the designer additional flexibility.

Another satellite design consideration is that the current IOSS does not have any sensing or collision avoidance capabilities and therefore care must be taken to ensure that there is a clear path from the ORU rack to each module to be serviced. This should not present any severe design constraints and future improvements to the IOSS can incorporate the necessary software and collision avoidance technologies for obstacle avoidance. The IOSS does avoid the problems of time delay inherent in real time control systems through local control during supervisory operation. The IOSS is also an existing system that has clearly demonstrated that remote servicing will be possible as the OMV becomes available.

1.1.2.2 FTS. The Flight Telerobotic Servicer is planned to be a multipurpose robotic system that allows a variety of uses and interfaces with several different supporting vehicles. One of its enabling objectives is to perform remote satellite servicing as an OMV smart front end. This system may consist of two or more seven degree of freedom arms. At least two of these arms may be highly dexterous and may be capable of interfacing with a variety of end effectors. It will start out as an advanced force reflecting teleoperator system and increase in autonomy until it becomes an intelligent robotic system. It is expected to have advanced sensing systems that may include



MODULE EXCHANGE OPERATION



IOSS INSERTING MODULE

Figure V–2: Module Exchange Operation Using the Integrated Orbital Servicing System force/torque, tactile arrays, position, proximity and an advanced vision system. It should be nearly equivalent to a suited astronaut in space and therefore capable of dexterous assembly and repair operations. This should ease some of the constraints on the designer when he is considering servicing design trades.

This system utilizes the natural intelligence inherent in man-in-the-loop operations. The FTS will be controlled by a human from a workstation located in the Space Station that may provide the operator an extensive array of sensory information from the remote worksite. In the initial phases of operation the operator manually controls the system but it is planned to gradually move towards autonomous operation as the necessary Artificial Intelligence (AI) and expert system technologies become available.

A potentially severe drawback to the extensive sensory feedback and teleoperation is the time delay due to the distance separating the operator from the worksite. Any sensory information received by the operator lags the input by at least 0.25 seconds. Studies done on teleoperator systems show that operator performance degrades severely with signal delays greater than 0.10 seconds and time delays for force reflecting systems tend to confuse the operator. This issue is being studied by NASA and they are looking at ideas such as letting the operator pre-plan the mission using a computer model and then letting the system carry out the operation in a supervisory mode with the operator being able to assume real time control in case of complications.

In its initial configuration the FTS may have the added flexibility of two arms which for example, may allow one arm to cut away a thermal blanket while the other pulls it away. It also may be highly dexterous which could remove some of the design constraints on the spacecraft/module interface and may have a higher probability of mission success because of the flexibility afforded by man-in-the-loop control. For example, if a piece of equipment has not deployed, the FTS operator would be able to observe this and could manually attempt a repair. In this instance two arms may beneficial, particularly if it is a highly dexterous operation. For most servicing operations however, one arm and an attachment device would be sufficient.

While the proposed FTS has many advantages, it is currently beyond the state of the art. Many of the required technologies are still in their infancy and the system is in its early development stage. There are still many control issues with the FTS such as teleoperator control with time delays, cooperative computer control of multiple manipulators and end point control with multiple sensory inputs that must be solved. When considering a servicing system, it should be remembered that the design process will lead the production by at least 5 years. Therefore, any features and technologies incorporated into the design must be sufficiently demonstrated at least five years prior to launch. This means that even if the FOC FTS exists by 2005, it will probably be 2010 before spacecraft will be fully FTS compatible.

1.1.2.3 IOSS Versus FTS. The IOSS in its present state is capable of performing a wide range of servicing tasks with a single arm. In addition, the IOSS is considerably lighter than the projections for the FTS. This is an important advantage as it reduces the amount of mass to be transported per servicing mission. The system can be upgraded to advanced control architectures using sensory feedback to enhance performance, to improve operator interface for improved real time control and to incorporate artificial intelligence and expert systems technologies as they reach maturity. The IOSS has the added advantage of being a proven system with a heritage of many successful demonstrations.

As the OMV and OTV become available the IOSS can be used as a first generation servicing system. Over time it can be upgraded and enhanced with advanced technologies until such time that the FTS has been fully developed and tested. At that point the FTS (or servicer based on FTS technology) would take over as the second generation servicing system. This approach would be more cost effective than forcing the FTS development to be geared to remote spacecraft servicing. Forcing the FTS to be the first generation remote servicer will place tremendous scheduling pressures to develop the required technologies.

1.1.3 Fluid Transfer

The refueling kit will be mounted on the OMV and consist of the tanks, pumps, umbilicals, remote fluid couplings, umbilical management system and structure. Many of the components will be similar to those found on the Orbital Spacecraft Consumables Resupply System (OSCRS) but the overall system will be much smaller. The capacity of OSCRS is considerably larger than necessary for the platform and the resulting mass penalty would preclude all of the necessary servicing from being completed with a single servicing mission. By using scaled down components a lighter system could be built at a relatively low cost and would allow all of the servicing to be completed on one mission.

Another possibility would be to scavenge the fuel from the OMV. This would reduce the mass of the refueling kit but may require the use of the propulsion module for additional fuel storage capacity. For missions not requiring delta velocity capability above that provided by the Short Range Vehicle (SRV), the added mass of the propulsion module will more than offset the mass savings by eliminating the fuel tanks from the fueling kit. (The SRV is a small version of the OMV.)

1.1.4 Equipment Not Available

The following pieces of equipment are currently being studied by NASA, but are judged to be not available in the time frame of this study (1995 – 2005):

i. the GEO-based OMV,

ii. the GEO Shack, and

iii. the man rated OTV.

These pieces of equipment are currently in the very early stages of development and may be available by 2010. The GEO-based OMV would reduce the mass of the servicing equipment that must be transported to GEO on each servicing mission and thus reduce the cost of servicing.

In order to maximize the efficiency of the GEO-based OMV, it should have its own dedicated IOSS. The OTV would then need only carry the refueling kit, fuel, and replacement units (ORUs) for the satellite being serviced. It is felt that this equipment is beyond the time period of interest for this study and therefore is not part of the servicing scenarios.

1.1.5 Space Station Services

The full operational capability Space Station will support satellite assembly and repair activities ranging from assembly of modular designs to final testing. The two modular satellite configurations presented here require varying levels of assembly at the Space Station while the business-as-usual configuration is assembled and tested on the ground. The assembly activities supported by the Space Station include:

- Subsystem level assembly
- Storage of modules, assemblies and subassemblies
- Testing of subsystems and systems
- Component level repair
- Deployment of appendages
- Inspection
- Fueling

1.2 Baseline Satellite Design

The study methodology is to compare the economic performance of modular satellite designs that can be fueled, serviced, and/or assembled on-orbit with a baseline business-as-usual satellite design. This subsection describes the non-modular design selected as the baseline satellite. The modular designs are described in Subsection V-2.

The baseline satellite design selected is the Ford FS-1300 shown in Figure V–3. It is a 3-axis design for the 1995 to 2010 time period, and has a hybrid payload of 24 C-band and 30 Ku-band transponders. It can be launched on the STS, Titan 4, or Ariane 4, and has a planned

Satellite Component	Mass (kg)
C-band transponders	72
C-band antenna	17
Ku-band antenna	26
Ku-band transponders	290
Total (Payload)	405
TT&C	16
Attitude control	59
Propulsion	107
Power	307
Thermal	122
Control Electronics	51
Structure	204
Harness	53
Mechanical Integration	24
Total (Bus)	943
Satellite dry mass	1,348
Propellant (12 years)	360
Satellite BOL mass	1,708
Apogee fuel (Ariane 4 launch)	1,093
Satellite GTO mass	2,801

Table V–1: Baseline Satellite Mass Summary

Satellite Subsystem	Power (W)	
	Solstice	Eclipse
C-band Transponders	660	660
Ku-band Transponders	3,345	3,345
Total (payload)	4,005	4,005
TT&C	30	30
Attitude control	113	96
Propulsion	2	2
Power	42	42
Thermal	131	75
Control electronics	80	80
Harness loss	44	43
Total (bus)	422	368
Battery Charging	133	0
Total spacecraft load	4,560	4,373
Solar array output (EOL)	4,390	0

Table V–2: Baseline Satellite Power Summary

life of 12 years. Although the baseline design is somewhat modular, it is not designed for remote servicing.

The major design characteristics of the baseline satellite are given in Table V-2. The mass summary is given in Table V-1, and the power summary for the baseline satellite is given in Table V-3.

A discussion follows of the satellite configuration, major subsystems, and satellite reliability. The discussion is divided into the following subsections:

1. Satellite Configuration
2. Attitude Control Subsystem
3. Propulsion Subsystem
4. Electrical Power Subsystem
5. Telemetry, Tracking, and Command
6. Control Electronics Subsystem
7. Thermal Control Subsystem
8. Structure and Mechanisms
9. Payload
10. Satellite Reliability

1.2.1 Satellite Configuration

The baseline configuration is developed for both STS and expendable launch vehicles. The design employs modular construction of bus and payload subsystems. The modular design allows the assembly and test of the spacecraft subsystems to be conducted in parallel which reduces the costs associated with these activities. Figure V–4 shows an exploded view of the baseline satellite showing its modular construction. Additional features of this configuration are as follows:

- Sunshade for radiator surfaces.
- Heat pipes in the north and south panels.
- Designed for maximum modularity and equipment accessibility.
- Designed for STS, Ariane 4 or Titan 4 launch vehicles.

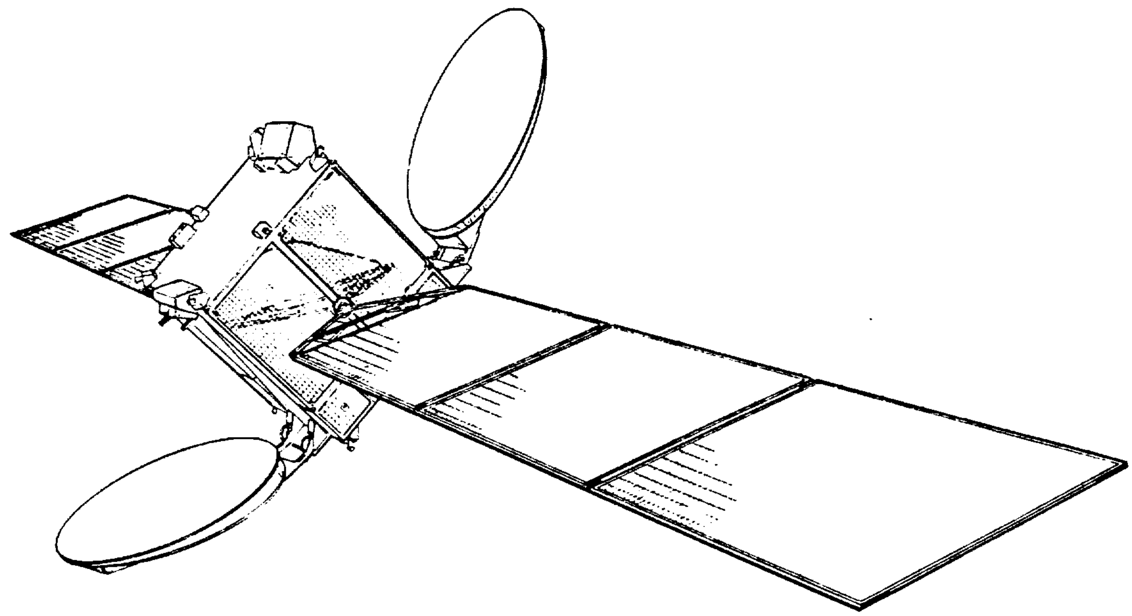


Figure V–3: Baseline Satellite Design (Ford FS-1300)

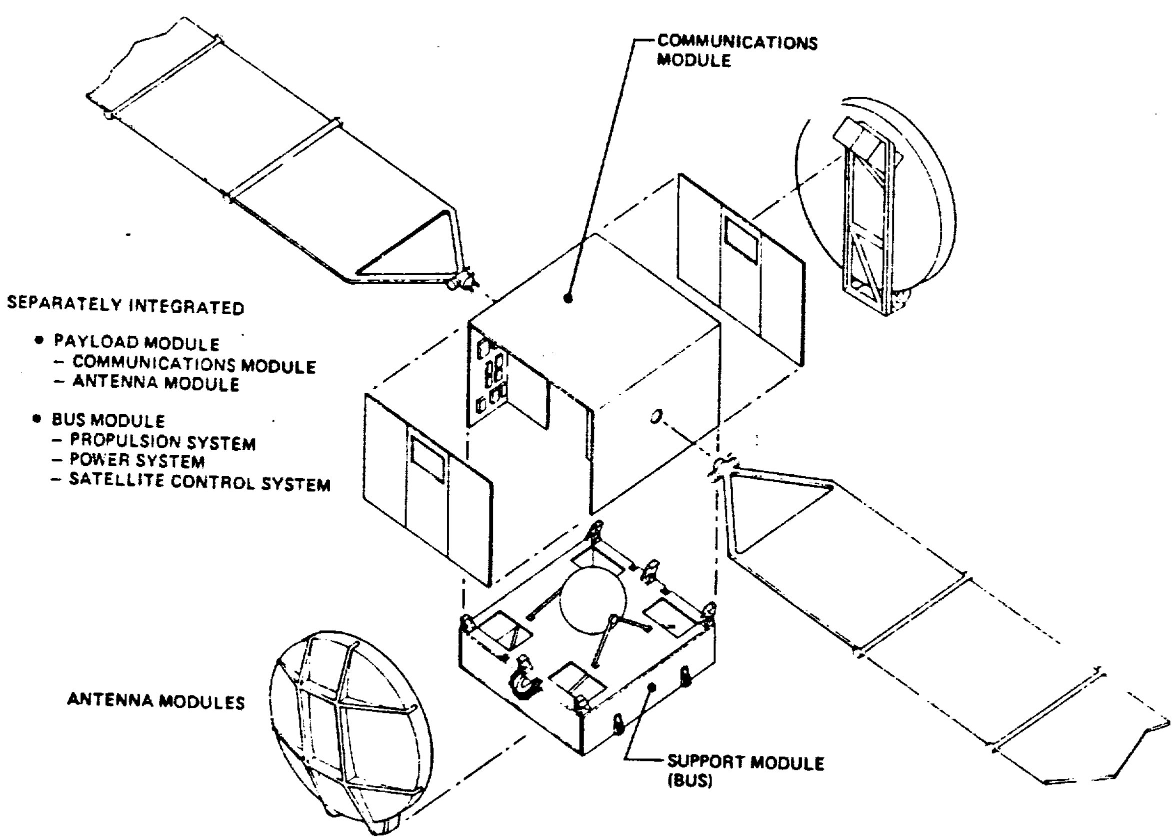


Figure V–4: Exploded View of Baseline Satellite Shows Construction

Manufacturer & model: Type: Lifetime: On-board switching: Launch vehicle:	Ford Aerospace, FS-1300 Hybrid communications satellite 12 yr Among coverage regions, also C- and Ku-bands interconnected. STS + upper stage or CELV.
Frequency band and bandwidth: – receive: – transmit:	C-band and Ku-band 5.925 – 6.425 and 14.0 – 14.5 GHz 3.700 – 4.200 and 12 – 12.75 GHz
Antenna – type: – number: – size: – mass: – coverage (2 C and 3 Ku beams): – polarization:	 Offset parabolic, dual gridded 2 1.4m x 1.8m C-band, 2.1m Ku-band 17 kg C-band, 26 kg Ku-band CONUS and E & W CONUS H and V linear for both bands
Transponders – number of C-band: – SSPA redundancy (C-band): – receiver redundancy (C-band): – number of Ku-band: – TWTA redundancy (Ku-band): – receiver redundancy (Ku-band): – mass: – dc power:	 24 each, 36 MHz bandwidth 6 for 5 3 for 2 30 each, 36 MHz bandwidth 5 for 4 4 for 2 72 kg C-band, 290 kg Ku-band 660 W C-band, 3,345 W Ku-band
Spacecraft – size (stowed): – mass, BOL (dry): – power (EOL) at summer solstice: – primary power – batteries: – attitude and station keeping: – attitude pointing accuracy: – apogee motor	 2.5m x 1.88 m x 2.6m 1,338 kg 4,560 W Solar cells (thin Si) 4 NaS, 262 Ah (total) 3-axis stab, biprop thrusters 0.10° 100N

Table V–3: Baseline Satellite (FS-1300) Design Characteristics

1.2.2 Attitude Control Subsystem

The attitude control subsystem consists of the sensors, actuators and processing electronics necessary to maintain the spacecraft in its proper orientation with respect to the sun and the earth. The attitude control system selected for the baseline design includes the following components and features:

Reaction Wheels – Two reaction wheels for correction of pitch and roll errors. Yaw controlled through passive coupling and magnetic torquers.

Magnetic Torquers – Roll/yaw magnetic torquers for control of yaw errors.

Earth Sensors – Sensing of pitch and roll errors during ascent through normal mode and station keeping maneuvers.

Sun Sensors – Determination of pitch and yaw errors during ascent and station keeping operations.

Ring Laser Gyros – Determination of absolute attitude and attitude rate information during ascent and station keeping operations.

Solar Array Drive Assembly – Clock driven stepper motors move the array panels to maintain maximum power output. Array power is passed to the main bus across slip rings.

1.2.3 Propulsion Subsystem

The propulsion subsystem is responsible for orbit insertion and maintenance and momentum wheel unloading. The propulsion system features are listed below.

Propellant – Bipropellant monomethylhydrazine, nitrogen tetraoxide system. Features I_{sp} of 290 seconds.

Tanks – Two tank system, one for for each propellant. Tanks are made of drawn titanium for decreased mass and oxidation. The tanks are mounted in the spacecraft central structure.

Plumbing – Valves, lines are made of titanium. Isolation valves ensure propellant containment during shuttle operations and emergencies.

Thrusters – 12 thrusters are used for station keeping and momentum unloading. Redundancy is provided by mounting thrusters in pairs.

1.2.4 Electrical Power Subsystem

The power subsystem provides for the generation, storage, regulation and distribution of electrical power. The power subsystem features are listed below:

Solar Arrays – Thin *n*-on-*p* silicon cells are used for mass reduction. Solar arrays provide primary power for bus and and payload subsystems during the non-eclipse phases.

Batteries – The batteries are used to store electrical energy for use during eclipse operations, clearing faults and for end-of-life operations where solar array power is insufficient to support the entire spacecraft load. Four NaS batteries provide 262 Ah of storage capacity.

1.2.5 Telemetry, Tracking, Command

The Telemetry, Tracking and Command (TT&C) subsystem provides for telemetry transmission, command receiving, and ranging signals. The telemetry formatting and modulation is performed in the Central Electronics Subsystem. The communications subsystem design allows simultaneous telemetry and ranging operations. A description of the subsystem is provided below.

Transponders – Ku-band transponders are used to transmit and receive the frequent telemetry and commands during transfer and synchronous orbit operations.

Antennas – The CONUS communication and omni-directional antennas are provided for transfer and synchronous orbit operations.

1.2.6 Control Electronics Subsystem

The Control Electronics Subsystem (CES) performs data processing functions, command decoding and telemetry formatting functions. The CES performs data processing and management functions for the power, attitude control, propulsion, thermal and payload subsystems. The CES is a 16 bit microprocessor based system with distributed microprocessors in the Remote Telemetry Units (RTU). The flexibility of the microprocessor based system allows for block commanding, higher levels of autonomy and improved attitude control performance through the ability to program attitude control subsystem. The components of the CES are described below.

Central processor unit (CPU) – Consists of memory boards, both read only and random access memory (ROM and RAM) and a 16-bit microprocessor. The CPU contains the main memory for the spacecraft and performs the main spacecraft control routines.

Data concentrator unit (DCU) – There are 2 DCUs which perform the control and command processing at the subsystem level. The DCUs are microprocessor based and contain some local memory.

Remote terminal units (RTU) – There are 3 RTUs that are responsible for telemetry gathering from the payload and sensors. Processing is limited to analog to digital conversion and smart control is derived from the DCUs.

Data bus – The data bus is a MIL-STD 1553B data bus which features low impedance and a favorable signal to noise ratio.

1.2.7 Thermal Control Subsystem

The thermal control subsystem provides active and passive thermal control for the payload and bus subsystems. The following elements and features are contained in the thermal subsystem:

Thermal Insulation – Multilayer blankets insulate the bus and payload subsystems from external variations in temperature. Insulation is placed on the bus, around propellant lines and thrusters and around solar array shunts.

Heat Pipes – Fixed conductance heat pipes are placed in the external spacecraft structure surrounding the transponders to provide heat dissipation and a thermal path to the radiators.

Thermal Coatings – White and black paints and optical reflectors are used to provide heat absorption and rejection for passive thermal control.

Heaters – Heaters are used to provide active thermal control for temperature sensitive components.

Battery Thermal Control– The sodium sulfur batteries require an operation temperature between 250° and 350° C. These temperature limits are maintained through a combination of variable conductance heat pipes and heaters. Variable conductance heat pipes were selected because of they are more reliable than louvers and heat valves. The entire battery thermal control system is contained within the battery module.

1.2.8 Structure and Mechanisms

The structure and mechanisms consist of the following items:

- Berylium central cylinder supports equipment panels forming a box.
- North-south panels are aluminum face skins over aluminum honeycomb.
- East-west panels are graphite face skins over aluminum honeycomb.
- Holddown and release units for solar array and antenna reflectors utilize pyrotechnic cable cutters and spring deployment motors.

1.2.9 Payload

The payload subsystem consists of the C and Ku-band transponders, waveguides, antennas, and other associated communications hardware. The payloads chosen provide Ku-band coverage for CONUS, Alaska and Hawaii, and C-band coverage for 90% of CONUS, Alaska, Hawaii and Puerto Rico. The basic components and their features are described below.

C-band Transponders – 24 C-band transponders are provided with 5/4 redundancy and 36 MHz bandwidth. The transponders feature 8.5 W solid state power amplifiers (SSPA) .

Ku-band Transponders – 30 Ku-band transponders are provided with 5/4 redundancy and 36 MHz bandwidth. The transponders use 50 W traveling wave tube amplifiers (TWTA).

Upconverters – The upconverters are used for Ku-band transponders. The upconverters are driven by master oscillators. Each set of master oscillators drives 8 upconverters.

Switch Matrix – Provide switching within and between C and Ku-bands.

Antennas – Two offset fed, dual gridded antennas are provided for transmitting and receiving C- and Ku-bands. The antennas are on the east and west faces of the spacecraft.

1.2.10 Spacecraft Reliability

Modern communications satellites are typically designed to last between 7 and 12 years, and by the 1990s the upper limit may go as high as 14 years. Current methods of increasing lifetimes involve added or improved redundancy and improvements in the quality of spacecraft components. Although these methods have been successful in the past, there are indications that lifetime extensions beyond 15 years require extensive redesign of the spacecraft to withstand the increased total dosage of radiation. The increase in mass and the design and manufacturing costs

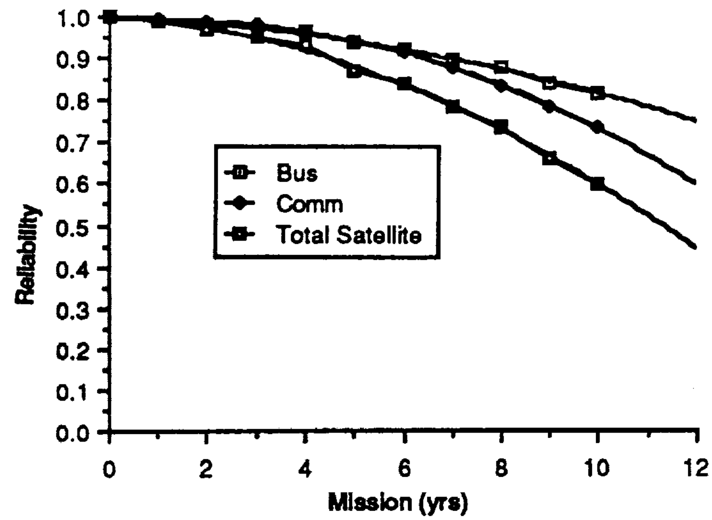


Figure V–5: Reliability for Baseline Satellite

involved in the redesign may be greater than converting to a serviceable spacecraft.

The composite reliability curve for the bus and payload components on the baseline satellite is shown in Figure V–5. At the end of its 12 year mission there is a probability of less than 50% that the entire spacecraft will be able to complete the mission. The biggest contributing factor to this figure is the payload. The probability of the payload being able to complete the mission is approximatedly 60% whereas the bus has an 80% probability of completing the mission.

TWTA failures account for a largest number of failures. As the Ku-band transponders transition from being TWTAs to SSPAs, the reliability of the payload can be expected to increase significantly.

The other major obstacle in extending satellite lifetimes is the hardening of electrical components, which requires extensive shielding and/or component redesign all the way down to the chip level. This will drive the cost of the satellite beyond that of a serviceable design and may not yield lifetime increases equal to those achievable with servicing.

1.3 Serviceable Components

An analysis of the baseline design is performed to determine which subsystems can be serviced by the hypothesized servicing infrastructure of

Subsection V-1.1. The subsystems are analyzed to determine

i. lifetime,

ii. failure modes, and

iii. possibility of being serviced.

The first two criteria are based on historical experience while the last is based on an evaluation of the individual subsystem designs.

The designs are analyzed to determine their adaptability to a modular design, the number and complexity of interfaces required, and compatibility with proposed robotic systems. Table V-4 shows the results of this analysis.

2 Modular Satellite Designs

The current trend in satellite manufacture is towards modularity. Modularity allows the assembly and test activities for the various subsystems to be performed in parallel and integrated as complete assemblies. As satellites become completely modular, they can be assembled on orbit at the Space Station and serviced remotely. In order to determine the benefits on orbit assembly and servicing, three modular satellite designs are developed:

1. The **Refuelable Satellite Design** is a slight modification to the baseline business-as-usual satellite that can be launched by ELV directly to GEO orbit. It is capable of being refueled in orbit.

2. The **Closed Architecture Design** is capable of being deployed and tested at the Space Station and serviced on orbit after an initial 12 year lifetime. It is capable of undergoing refueling and replacement of life-limited payload equipment with the exception of solar arrays.

3. The **Open Architecture Design** is capable of being transported to LEO in pieces, assembled and tested at the Space Station, and serviced on orbit after an initial 12 year lifetime. It is capable of undergoing refueling and replacement of life-limited payload equipment with the exception of solar arrays. In addition it is capable of on-orbit storage of degraded or failed orbital replacement units.

2.1 Refuelable Satellite Design

The baseline non-modular configuration described in Subsection V-1.2 is modified to allow the possibility of refueling to extend the lifetime. This configuration allows the number of transponders to be increased – from 24 to 30 C-band and from 30 to 35 Ku-band transponders. The satellite mass summary is given in Table V-5, and the power summary is given in Table V-6.

The modifications to the baseline satellite described in Table V-2 are as follows.

- The amount of station keeping fuel is reduced to a 8 yr supply from a 12 yr supply, thus saving 116 kg in mass.
- 5 Ku-band and 6 C-band transponders can be added using the fuel mass savings.
- An additional 779 W power is required for these transponders.
- Increased thermal subsystem capacity is required to offset the increased heat dissipation.
- The propulsion subsystem and structure are modified to include remote fluid couplings and an OMV docking interface which allows the satellite to be fueled by the OMV and remote servicer.
- Lifetime is increased from 12 to 14 years.

2.2 Closed Architecture Design

The closed architecture modular design is based on the traditional closed architecture of the baseline satellite described in Subsection V-1.2. The main bus is fully integrated on the ground and launched to the Space Station on an ELV or the STS. At the Space Station the appendages are deployed and system level tests are performed, and the OTV is used to transport the satellite to geosynchronous orbit.

Bus Component	Life Limitations	Cycle Limitations	Consumable Limitations	Technology Limitations	Servicing Required?
Structure				Material properties.	None
Propulsion					
Tanks	Blocked orifices		Fuel		Refuel
Fuel lines	Clogged lines				None
Thrusters	Blocked orifices	Worn valves		I_{sp} of fuel	None
Power					
Generation	Radiation	Thermal cycles of connections.		Cell efficiency	None
Storage	Cell depletion			Batteries; NiH and NaS.	Replace
Distribution	Cycling of relays			Converter design	Replace
Attitude Control					
Sensors	Sensor degrades	Moving parts wearout.		Sensors	Replace
Actuators		Moving parts wearout.			Replace
TT&C	Aging of electronics			Solid state designs, transmitter.	None
Thermal	Aging of coatings and blankets				None
Central electronics	Aging of electronics			Data storage, microprocessors	Replace
Solar array drive		Moving parts wearout.			None
Payload					
Antennas				Materials	None
Transponders	TWTA wear out SSPA aging	Infant failure		Replace TWTAs with SSPAs.	Replace

Table V–4: Analysis of Serviceable Components on Baseline Satellite

Satellite Component	Mass (kg)
C-band transponders	86
C-band antenna	17
Ku-band transponders	344
Ku-band antenna	26
Total (Payload)	473
TT&C	16
Attitude control subsystem	59
Propulsion subsystem	75
Power subsystem	335
Thermal subsystem	132
Control electronics subsystem	51
Structure	204
Harness	55
Mechanical Integration	24
Total (Bus)	951
Dry spacecraft mass	1,424
Propellant (8 years)	244
Spacecraft BOL mass	1,668
Apogee Fuel (Ariane 4 launch)	1,062
Satellite GTO mass	2,730

Table V-5: Mass Summary - Refuelable Satellite

Satellite Component	Power (W)	
	Solstice	Eclipse
C-band transponders	770	770
Ku-band transponders	4,014	4,014
Total (Payload)	4,784	4,784
TT&C	30	30
Attitude control subsystem	113	96
Propulsion subsystem	2	2
Power subsystem	22	42
Thermal subsystem	131	75
Control electronics	80	80
Harness loss	44	43
Total (Bus)	422	368
Battery charging	156	0
Total load	5,362	5,152

Solar array power (EOL)	5,290	0

Table V-6: Power - Refuelable Satellite

Satellite Component	Mass (kg)	
	Years 1-12	Years 12-24
C-band transponders	72	72
C-band antenna	17	17
Ku-band transponders	336	290
Ku-band antenna	26	26
Total (Payload)	451	405
TT&C	16	16
Attitude control subsystem	64	64
Propulsion subsystem	75	75
Power subsystem	335	327
Thermal subsystem	134	134
Control electronics	51	51
Structure	390	390
Harness	65	65
Mechanical integration	66	66
Total (Bus)	1,196	1,188
Total satellite (dry)	1,647	1,593
Propellant (12 years)	436	421
Total satellite (BOL)	2,083	2,014

Table V-7: Mass Summary - Closed Design

The mass summary for this configuration is given in Table V-7, and the power summary is given in Table V-8 The closed architecture satellite design is shown in Figure V-6. Figure V-7 shows the subsystem modules and the satellite structure.

The description of the closed architecture design is divided into the following subsections:

1. Configuration
2. Attitude Control Subsystem
3. Propulsion Subsystem
4. Electric Power Subsystem
5. Telemetry, Tracking, Command
6. Control Electronics Subsystem
7. Thermal Control Subsystem
8. Payload
9. Structure and Mechanisms

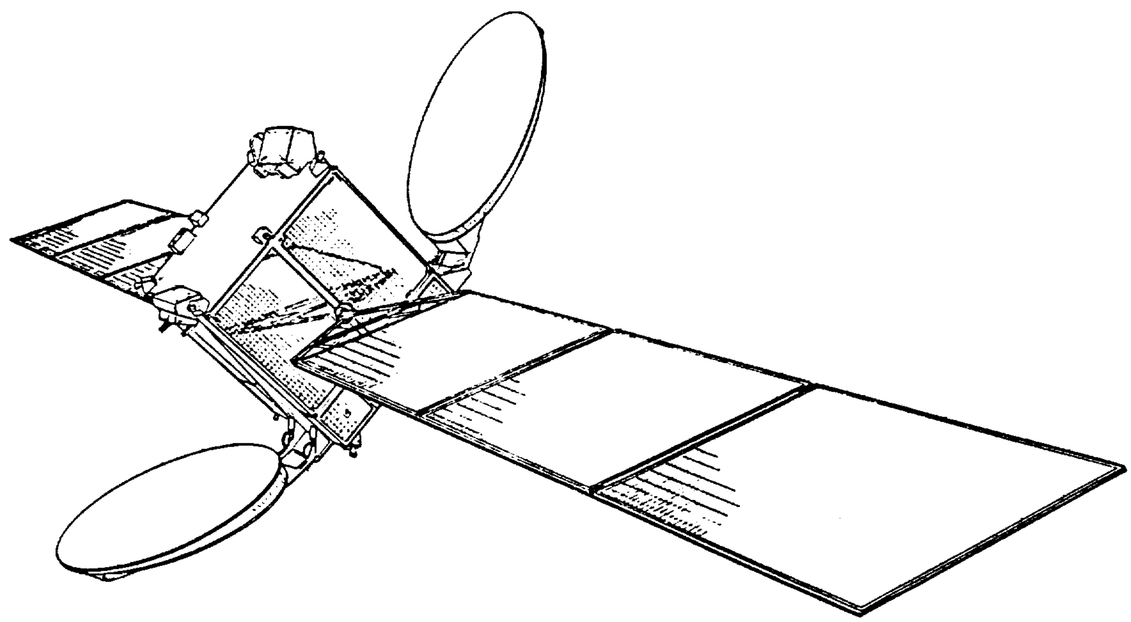


Figure V–6: Closed Architecture Satellite

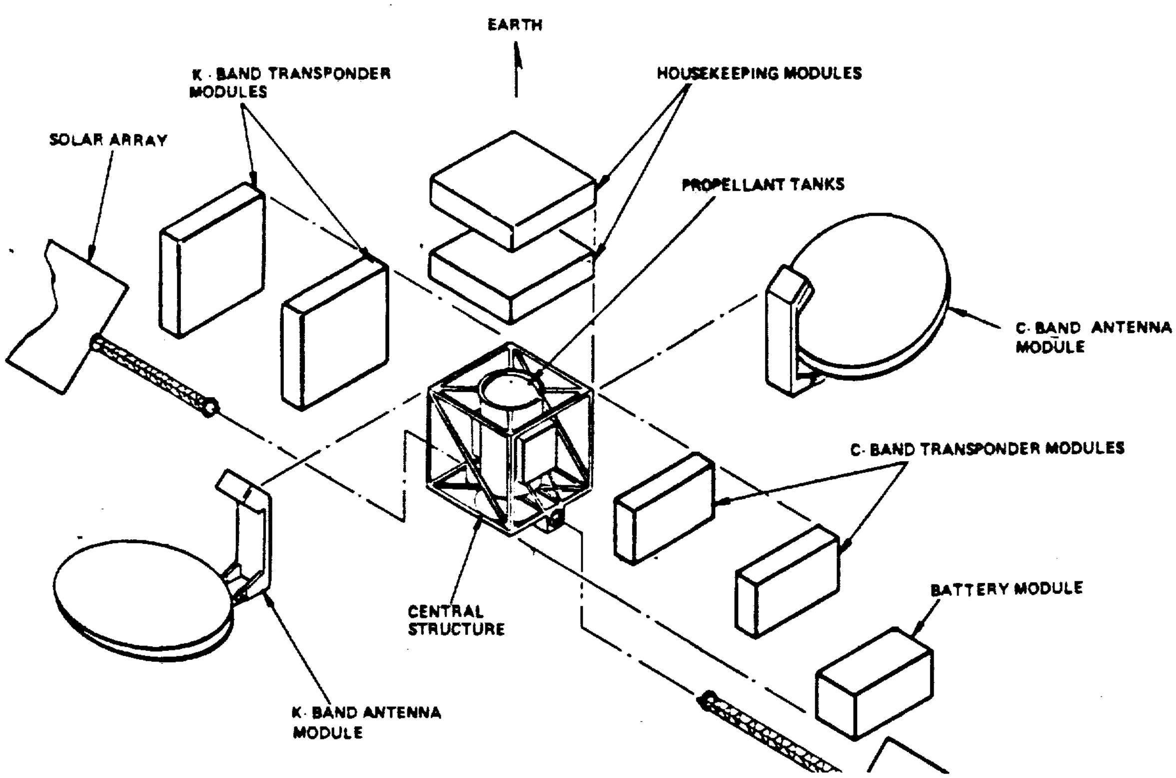


Figure V–7: Exploded View of Closed Architecture Satellite Shows Modularity

Satellite Component	Power (W) Years 1–12 Solstice	Power (W) Years 1–12 Eclipse	Power (W) Years 12–24 Solstice	Power (W) Years 12–24 Eclipse
C-band transponders	660	660	660	660
Ku-band transponders	3,791	3,791	3,345	3,345
Total (Payload)	4,451	4,451	4,005	4,005
TT&C	30	30	30	30
Attitude control subsystem	113	96	113	96
Propulsion subsystem	2	2	2	2
Power subsystem	42	42	42	42
Thermal subsystem	131	75	131	75
Control electronics subsystem	80	80	80	80
Harness loss	44	43	44	43
Total (Bus)	422	368	422	368
Battery Charging	146	0	133	0
Total satellite load	5,019	4,819	4,560	4,373
Solar array capacity (EOL)	4,877	0	4,450	0

Table V–8: Power Summary for the Closed Architecture Satellite

2.2.1 Configuration

The configuration for the closed architecture design is determined from the analysis of the serviceable components described in Subsection V-1.3 and a reliability analysis. Based on the capabilities of the anticipated remote servicing systems described in Subsection V-1.1.2, the satellite was initially divided into modules according to subsystems. The spacecraft components were analyzed to determine the range of serviceable components and the number of subsystem modules required. It was found that the increased mass of the structure, hardware, and thermal subsystems required to support discrete subsystem modules offsets the advantage of increased flexibility in servicing.

Thus the decision was made that the spacecraft is to be composed of composite modules that may contain components of several subsystems. The selected configuration utilizes four modules which contain the following equipment:

i. Ku-band payload components in a single module on the north facing panel.

ii. C-band components in a single module on the south panel.

iii. Batteries in a second module on the south facing panel.

iv. Bus subsystem in a single module on the earth facing panel. (The bus module contains the attitude control equipment.)

These modules are the orbital replacement units (ORUs) that can be serviced.

2.2.2 Attitude Control Subsystem

The effect of modularity on the baseline configuration is to increase the dry mass of the spacecraft, which in turn increases the moments of inertia and the effects of the gravity gradient. The asymmetrical antenna configuration results in disturbances about the roll axis due to solar pressure imbalances. The combination of the increase in the secular and cyclic torques must be offset by an increase in the sizes of the momentum wheels and magnetic torquers. However, this results in only a minor increase in size, and the attitude control system remains basically unchanged from the baseline.

All components contained in the Attitude Control Subsystem (ACS) are replaced after twelve years with the exception of the solar array drive assembly. Adequate redundancy is provided in the solar array drives to complete the 24 year mission. The ACS components (except the solar array drives) are contained in the earth facing panel and are replaced as an entire assembly.

2.2.3 Propulsion Subsystem

The spacecraft is placed into geosynchronous orbit by the OTV, which eliminates the need for a large apogee kick motor and reduces the mass of the propulsion subsystem.

Based on tradeoff studies, it is decided to use a bipropellant system. Mono and bipropellant systems were compared – over a 24 year mission a bipropellant system saves 72 kg of station keeping fuel versus a monopropellant system while only adding 21 kg mass. The bipropellant system can be refueled with fuel scavenged from the OMV bipropellant tanks. This eliminates having to carry additional fuel tanks or the Orbital Spacecraft Refueling System (OSCRS), which in turn reduces the servicing mission transportation costs.

The propulsion subsystem contains remote fueling couplings similar to designs proposed by Fairchild and Moog, but does not have any significant changes to its topology. Replacement of the lines, isolation valves, and thrusters is not necessary since these components should be able to last the entire 24 year mission.

2.2.4 Electrical Power Subsystem

The only significant change to the power subsystem is in the design of the solar arrays for a 24 yr mission. This requires increased solar cell area and cover glass thickness to offset the increased degradation of a 24 yr versus 12 yr mission. Non-regulated and partially regulated buses were evaluated but the increase in mass offsets the advantage gained in the flexibility inherent in these systems.

2.2.4.1 Solar Array Alternatives. Several types of arrays were considered as alternatives to silicon cells. One alternative was to use different cells such as gallium arsenide (GaAs) or Indium Phosphide. The GaAs cells are approximately 50% more radiation resistant than silicon cells, which implies that less degradation margin is required. Current data indicates that the power to mass ratio (W/g) for GaAs is 50% less than that of the projected thin silicon cells. In addition, GaAs cells are several times more expensive than silicon cells.

There is not sufficient data to evaluate the indium phosphide cells, but current data indicates that they do not experience severe radiation degradation. As this technology matures, it may be a viable alternative.

The final alternative considered is a roll out type solar array. In this configuration the array is partially deployed at launch, but a portion of the array remains protected in a storage canister that provides shielding. As the array degrades, additional array is deployed to increase the power output. However, the additional mass and added complexity of this type solar array offsets the advantage of the reduced degradation.

2.2.4.2 Use of Power Margin. In order to compensate for degradation and/or failure of the solar cells, additional array area must be added to compensate for the lower output at the end of life. This results in a large power margin during the first 12 years as shown in Figure V–8. This power margin can be used to support up to 4 additional Ku-band transponders during the first 12 years. When the satellite is serviced in year 12, the Ku-band payload is replaced with a payload package containing only 30 transponders. The power curves for the revised scenario are shown in Figure V–9. In order to support the load during eclipse, slightly larger batteries are required during the first 12 years. During the servicing mission the batteries are replaced with the standard size batteries.

2.2.4.3 Batteries. The batteries and control electronics for the power subsystem are exchanged after 12 years. The batteries are contained in a separate module on the south panel. The power control electronics and regulators are

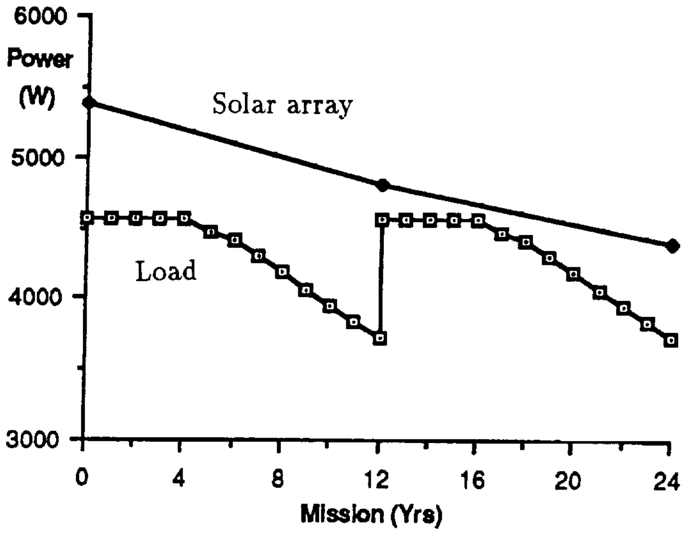


Figure V-8: Power – Uniform Load

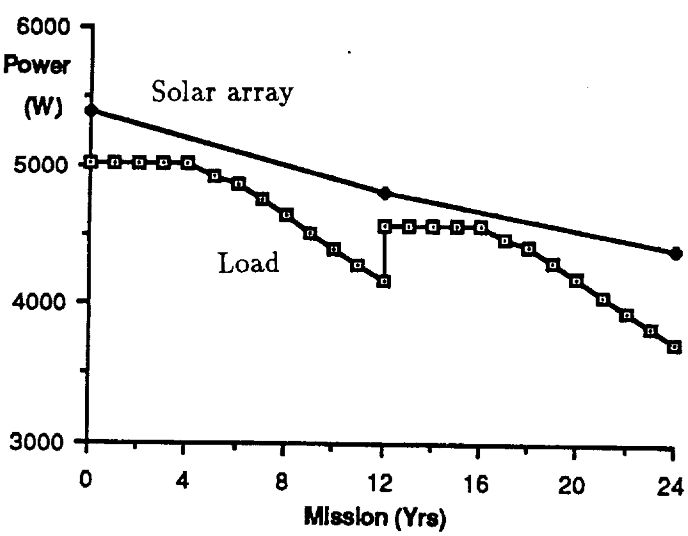


Figure V-9: Power – Added Transponders

contained in the house keeping module on the earth facing panel. The shunt regulators are not replaced since they will last the entire mission.

During the initial phase of operation, there is a large power margin. In order to maintain the bus voltage within 42 ±15 V dc, it is necessary to dissipate the excess power. During the initial operation period, power regulation is provided by shunt and switching regulators. As the arrays degrades, additional strings could be switched in and/or dissipative loads removed.

2.2.5 Telemetry, Tracking, Command

The Telemetry, Tracking, and Command (TT&C) subsystem remains unchanged from the baseline design. The TT&C transponders and electronics are replaced after 12 years. The TT&C components are contained in the house keeping module on the earth facing panel.

2.2.6 Control Electronics Subsystem

There are no changes to the Control Electronics Subsystem (CES) from the baseline design. The CES components are contained in the house keeping module and are replaced after 12 years.

2.2.7 Thermal Control Subsystem

Modularity significantly affects the thermal subsystem since heat transfer across modules is very difficult to achieve. Each module is thermally isolated from the others, and independent thermal control is required for each module. Thermal isolation is achieved by insulating the modules with multilayer thermal blankets. The heat pipes and associated radiators are built into the communication payload modules and are replaced with their respective modules. The heaters and thermal blankets contained in the various modules are replaced with the modules. Heaters and insulation for the propulsion subsystem are not serviced, and therefore sufficient redundancy is provided to complete the entire 24 year mission.

2.2.8 Payload

The only changes to the payload are to the antennas and the initial number of Ku-band transponders. The antennas are designed for manual deployment at the Space Station and therefore do not have any deployment mechanisms. The number of Ku-band transponders is increased to 34 for the initial 12 years to utilize the excess power availability in the first half of the mission. With the exception of the antennas and their associated feeds and waveguides, the entire communications payload is to be replaced after 12 years. The Ku-band and C-band transponder components are contained in modules on the north and south panels, respectively.

2.2.9 Structure and Mechanisms

The closed architecture satellite is designed to be integrated on the ground and launched to the Space Station as a complete unit. This means that the structure must be capable of withstanding launch loads encountered during a Shuttle or CELV launch. The deployed spacecraft must be capable of withstanding 0.1 G transfer orbit loads.

The satellite is placed into geostationary orbit by the OTV and therefore must have an OTV compatible interface. A concept for an OTV interface is shown in Figure V–10. In addition, docking interfaces are required for the OMV. The OMV docking interface is shown in Figure V–11. Access ports for servicing are required on the earth facing module and either the east or west facing module.

The satellite is designed for deployment and checkout at the Space Station. Therefore, the antenna and solar arrays do not have deployment mechanisms. They are instead designed for deployment by the Flight Telerobotic Servicer (FTS).

In addition, the satellite is designed for remote servicing by the Integrated Orbital Servicing System (IOSS). The IOSS allows a great deal of flexibility in the design of the spacecraft/ORU interface. One of the candidate designs developed by Martin Marietta is shown in Figure V–12.

The satellite also has external EVA grapple points for handling at the Space Station, and the design must be compatible with EVA Design Criteria (JSC-10615).

The additional scarring for handling at the Space Station and remote servicing imposes mass penalties on the mechanical integration components and the structure. The net effect of the required design modifications for this scenario is a 17% increase in the spacecraft dry mass. The predominate mass increases are in the structure and power subsystem.

2.3 Open Architecture Design

The open architecture modular design allows subsystem level assembly at the Space Station and allows payload redundancy to be added and bus components to be replaced at the end of 12 years. Used and/or failed ORUs are stored on the satellite, eliminating the need for de-orbiting used components.

The individual subsystems are integrated on the ground and launched to the Space Station as modules. Final assembly and system level tests are performed at the Space Station.

The mass summary for this configuration is given in Table V–10, and the power summary is given in Table V–9 The open architecture satellite design is shown in Figure V–13. Figure V–14 shows the subsystem modules and the satellite structure.

The description of the open architecture design is divided into the following subsections:

1. Configuration
2. Attitude Control Subsystem
3. Propulsion Subsystem
4. Electric Power Subsystem
5. Telemetry, Tracking, Command
6. Control Electronics Subsystem
7. Thermal Control Subsystem
8. Payload
9. Structure and Mechanisms

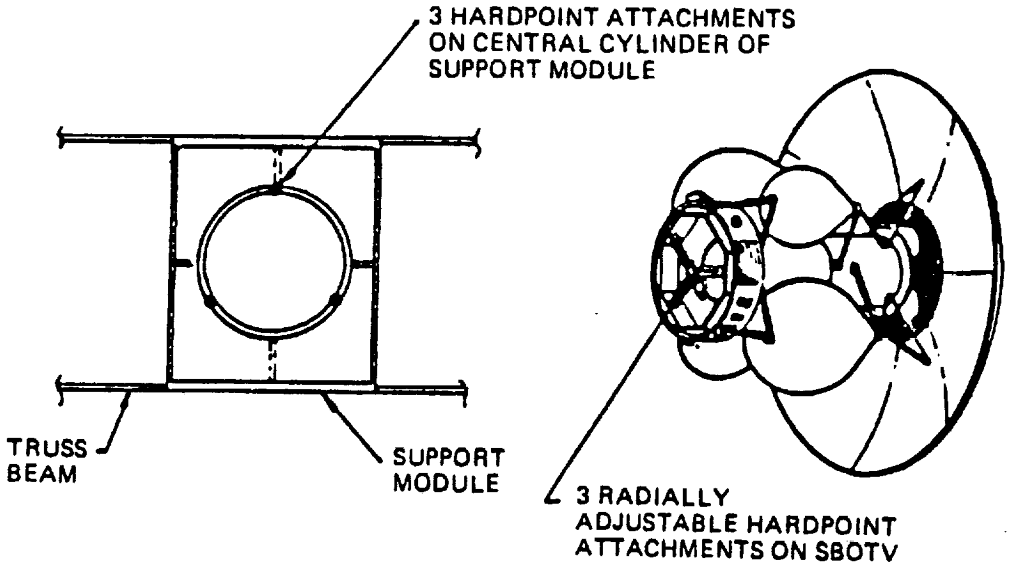


Figure V–10: OTV/Satellite Interface

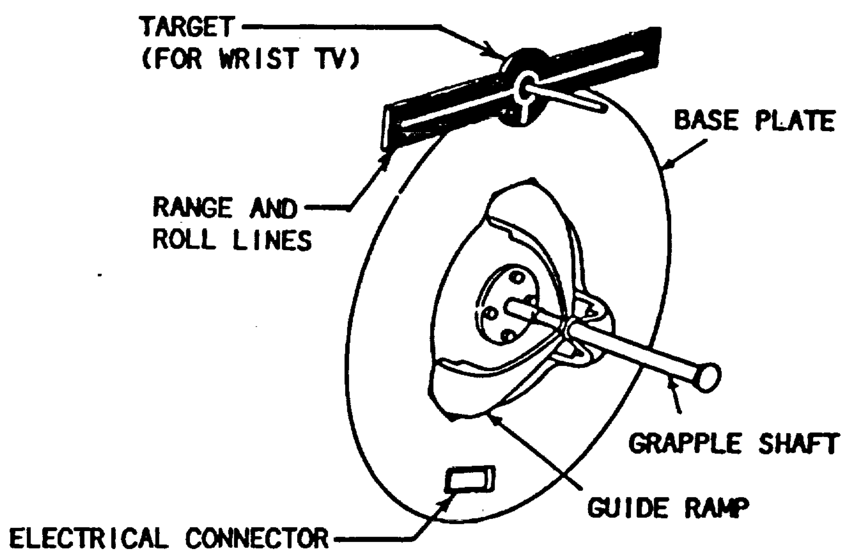


Figure V–11: OMV Docking Interface

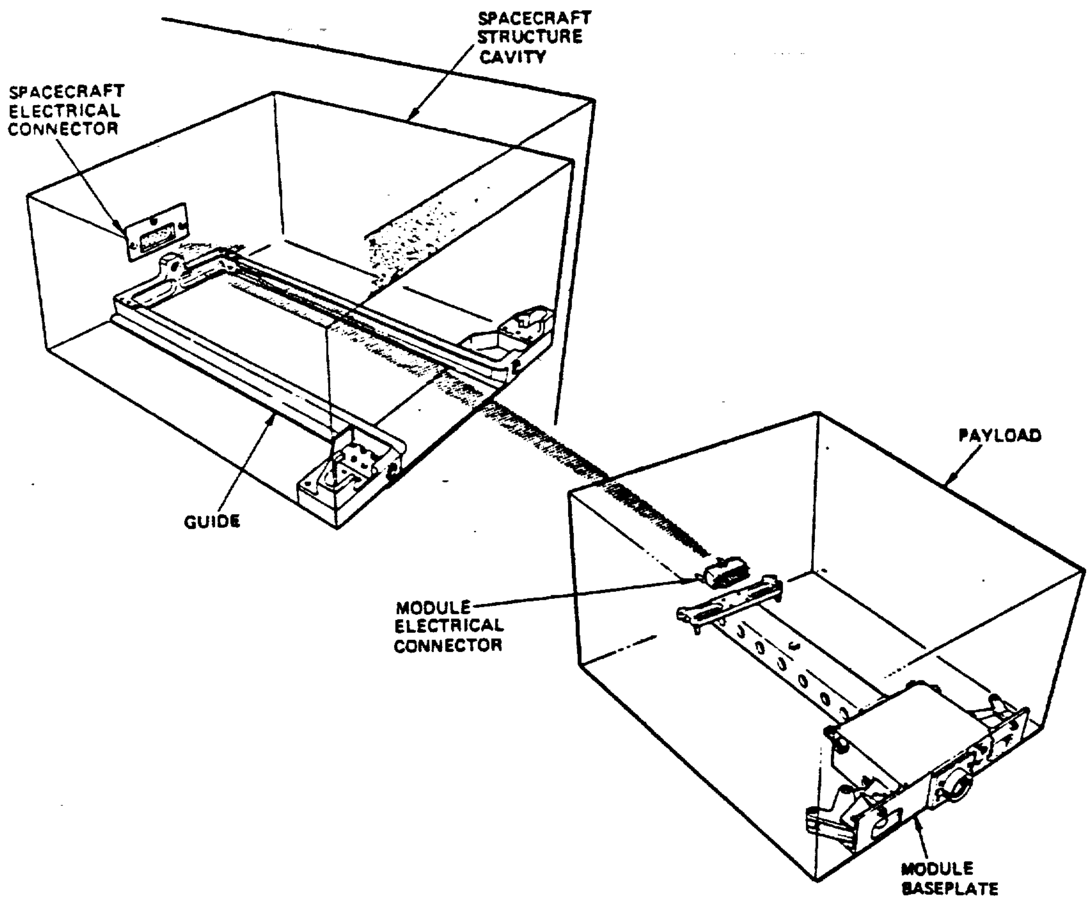


Figure V–12: ORU/Satellite Interface

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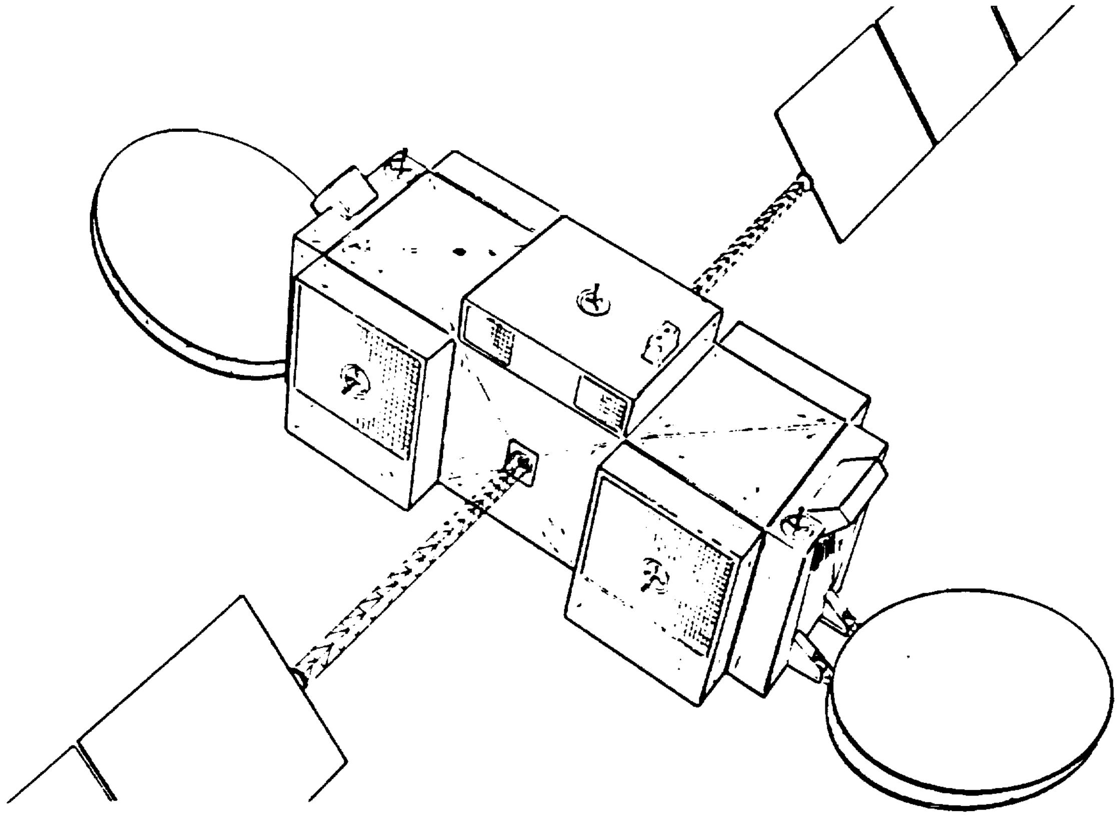


Figure V–13: Open Architecture Satellite

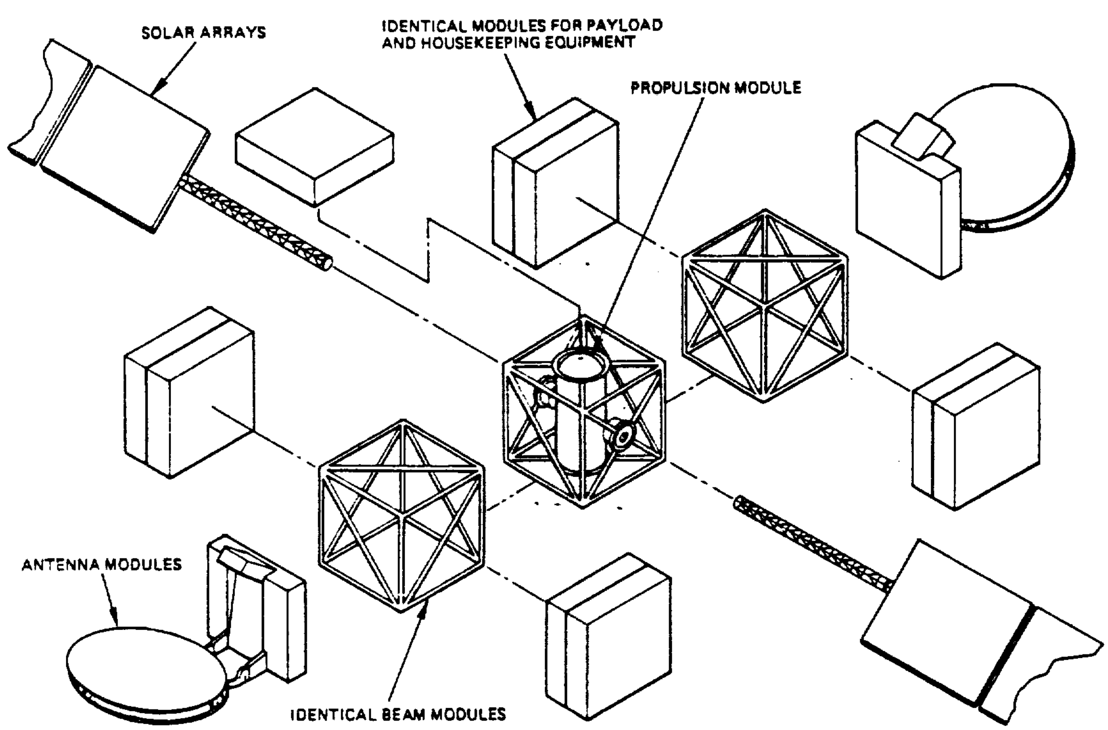


Figure V–14: Exploded View of Open Architecture Satellite Shows Modularity

Satellite Component	Power (W) Years 1–12 Solstice	Eclipse	Years 12–24 Solstice	Eclipse
C-band transponders	660	660	660	660
Ku-band transponders	3,791	3791	3,345	3,345
Total (Payload)	4,451	4,451	4,005	4,005
TT&C	30	30	30	30
Attitude control subsystem	113	96	113	96
Propulsion subsystem	2	2	2	2
Power subsystem	42	42	42	42
Thermal subsystem	131	75	131	75
Control electronics subsystem	80	80	80	80
Harness loss	44	43	44	43
Total (Bus)	422	368	422	368
Battery Charging	146	0	133	0
Total satellite load	5,019	4,873	4,560	4,373
Solar array capacity (EOL)	4,877	0	4,450	0

Table V–9: Power Summary for Open Architecture Satellite

2.3.1 Configuration

The configuration for the open architecture design allows final assembly at the Space Station. The configuration is a truss structure consisting of 3 m graphite epoxy truss elements with a graphite epoxy central cylinder mounted in the center truss section. The entire truss assembly is encased in multilayer thermal insulation to minimize thermal distortions. The subsystem and payload modules are affixed to the truss structure via IOSS-compatible interface mechanisms.

The open architecture provides for future growth through the addition of payload modules during a scheduled servicing operation. The bus is scarred to provide storage for the used house keeping ORUs, and therefore eliminates the need for disposal of servicing debris.

The configuration consists of the following modules:

i. Ku-band payload components are mounted in a single module on the north panel of the west end of the truss assembly.

ii. C-band payload components are mounted in a single module mounted on the north panel of the east end of the truss assembly.

iii. Batteries are mounted in a single module on the north panel of the truss structure on the east end of the truss assembly.

iv. House keeping equipment is in two modules attached to the earth facing panel of the center truss section. (Includes attitude control equipment.)

v. A non-replaceable central cylinder module contains the propellant tanks, OTV interface and truss structure for the center truss section.

These modules are the orbital replacement units (ORUs) that can be serviced, with the exception of item v.

The open architecture satellite is designed to be assembled with a minimum amount of EVA. The truss structure for the central section of the bus and the subsystem modules are transported to the Space Station as complete assemblies. The remaining truss structure and thermal blankets are completely assembled and integrated at the Space Station. This configuration also has the necessary interfaces for the OMV and the OTV as described in Subsection V-2.2.9 for the closed architecture satellite, and is compatible with EVA design criteria.

Satellite Component	Mass (kg) Years 1–12	Years 12–24
C-band transponders	72	72
C-band antenna	17	17
Ku-band transponders	336	290
Ku-band antenna	26	26
Total (Payload)	451	405
TT&C subsystem	16	16
Attitude control subsystem	66	72
Propulsion subsystem	75	75
Power subsystem	335	322
Thermal subsystem	147	147
Control electronics subsystem	51	51
Structure	533	533
Harness	70	70
Mechanical Integration	52	52
Total (Bus)	1,345	1,338
Stored mass	0	811
Total satellite (dry)	1,796	2,554
Propellant (12 years)	476	686
Total satellite (BOL)	2,272	3,240

Table V–10: Mass Summary - Open Design

2.3.2 Attitude Control Subsystem

The attitude control subsystem is similar to the baseline configuration described in Subsection V-1.2.2, and consists of momentum wheels and magnetic torquers. Only the size of the actuators is scaled up to account for the changes in the moments of inertia. The attitude control actuators are mounted in the innermost house keeping module and are replaced after 12 years. The replacement components also are scaled up to account for the increase in inertia after servicing. The control software and algorithms are also modified in the replacement components to account for the change in the dynamics of the spacecraft.

2.3.3 Propulsion

The changes to the propulsion system are similar to those discussed in Subsection V-2.1.3 for the closed architecture satellite. The only additional change is the provision for added propellant capacity to account for the increased propellant consumption following the servicing mission. Servicing of the propulsion system is limited to the replenishment of the liquid propellants.

2.3.4 Electrical Power Subsystem

The electrical power system remains unchanged from the baseline and the closed architecture designs. Additional solar array capacity is provided to offset the effects of degradation and to provide increased capacity for the additional transponders added during the servicing mission.

The batteries and converters are the only elements of the electrical power subsystem that are serviced. The batteries are replaced with a new assembly placed on the south end of the truss.

2.3.5 Telemetry, Tracking, Command

The TT&C subsystem remains unchanged from the baseline design. The TT&C subsystem components are contained in the house keeping modules and are exchanged after 12 years.

2.3.6 Control Electronics Subsystem

There are no changes to CES from the baseline design. The CES components are contained in the house keeping module and are replaced after 12 years.

2.3.7 Thermal Control Subsystem

The changes to the thermal control subsystem are identical to those made for the closed architecture satellite described in Subsection V-2.2.7.

2.3.8 Payload

The payload is similar to that for the closed architecture satellite described in in Subsection V-2.2.8. It is completely modular with separate modules for the C-band and Ku-band transponders and antennas.

The entire payload is to be replaced and upgraded after 12 years life. The additional transponder and switching packages are placed on the east and west ends of the satellite directly opposite the original units. Additional waveguide switches are required to prevent rf leakage during the first twelve years life. Additional switching capacity is also required to provide interconnections between the primary and replacement units.

The replacement components are added during the servicing mission and could operate in parallel with the functional transponders in the primary payload. According to reliability curves for typical communications systems, it is estimated that 26 C-band and 21 Ku-band transponders will be functional after 12 years of operation. At the 12-year servicing mission an additional 24 C-band and 30 Ku-band transponders are added, yielding a total capacity of 50 C-band and 51 Ku-band transponders.

The only part of the payload that is not serviced is the antennas. The antennas are designed for a 24 year mission lifetime.

2.3.9 Structure and Mechanisms

The basic structure of the spacecraft is a graphite epoxy truss structure with a central cylinder to provide an adequate load path during launch. The assembled structure is sized for launch loads up to 0.1 G. This figure is based on previous experience with geostationary platform studies and deployed load capacities of solar arrays.

The ORU/module interfaces, solar arrays, and antennas are permanently attached to the structure. Additional mechanical, power, wave guide, and data interfaces are provided for the replacement modules on the south panels of the bus. Mechanical interfaces are provided on the earth facing panels for storage of the spent house keeping modules. The configuration also includes the appropriate scars and interfaces required by the servicer and OMV as discussed in Section V-2.2.9.

The satellite is designed for complete assembly, deployment, and test at the Space Station and therefore does not contain any deployment mechanisms. The design complies to the guidelines specified for EVA Design Criteria.

3 Assembly and Launch Operations

Assembly and launch operations are explained for the different satellite designs.

3.1 Introduction

The baseline non-modular (Subsection V-1.2) and refuelable modular (Subsection V-2.1) satellite designs can be launched on either an expendable booster or the STS. The BOL wet mass of these satellites is 1,665 kg which is within the capabilities of several expendable boosters or an TOS and STS combination. The launch costs are shown in Table V–11. The figure for the Ariane scenario assumes a slight expansion in the launch capacity of the Ariane 4 to allow a dual launch.

The baseline satellite does not use the Space Station as a transportation node and therefore is not designed to utilize the services provided by the Space Station. Both the closed and open

Capital Expenditure Item	Cost ($M, 1987) Ariane 4	STS/TOS	ILV/OTV
Spacecraft cost	64.2	64.2	64.2
Transportation charges	40.0	42.3	34.2
OMV/OTV costs	–	–	6.1
Space Station support	–	–	1.6
Mission operations	2.6	2.6	2.6
Launch insurance	27.0	27.3	13.5
Totals	133.8	136.4	122.2

Table V–11: Transportation Charges for Baseline or Refuelable Satellites

architecture satellites are designed for assembly, deployment, test, and launch from the Space Station.

The assembly and launch scenarios are developed assuming that the following services are provided:

- Rendezvous and docking system for the STS.
- Mobile Remote Manipulator System (MRMS)
- Storage/transfer facility for monopropellant hydrazine, mono-methyl hydrazine (MMH), nitrogen tetra-oxide (NTO), liquid hydrogen, liquid oxygen and nitrogen gas.
- Environmentally controlled storage area in the Customer Servicing Center (CSC).
- CSC contains interfaces to the Space Station power and data management systems.
- Space Station based OMV and OTV.
- An operational Flight Telerobotic Servicer (FTS).
- A communications system capable of providing a link between a ground control facility and the satellite.
- Extra Vehicular Activity (EVA) support equipment and standard tools.
- Video and communications links between pressurized module and the CSC.
- Antenna range test equipment.

3.2 Closed Architecture Design

The closed architecture satellite (also known as the FS-1300 M1) presented in Subsection V-2.2 is designed to be launched to the Space Station as an integrated unit on expendable booster such as the Atlas H, the Industrial Launch Vehicle (ILV), or the STS. The spacecraft is deployed and checked out at the Space Station and then transported to GEO by the OTV. The complete transportation, deployment, test and launch scenario is shown in Table V–12 and is described below.

3.2.1 Transportation to Space Station

The spacecraft is launched to low earth orbit (LEO) on either an expendable booster or the STS. If the shuttle is used, the spacecraft is transported directly to the Space Station. After the shuttle has docked to the Space Station the cargo bay is unloaded by the Mobile Remote Manipulator System (MRMS). The MRMS then transports the spacecraft to the Customer Servicing Center (CSC) for deployment and checkout.

If an expendable booster is used, the spacecraft is placed into a parking orbit outside the Space Station control zone. The space-based OMV (SB-OMV) is dispatched to retrieve the spacecraft from the parking orbit. Because the rate of nodal regression is greater for lower altitude orbits, the OMV must retrieve the payload from the launch vehicle as soon as possible to avoid costly plane change maneuvers.

The OMV grapple fixture is attached to a com-

1.	Launch stowed satellite on a shared Shuttle flight to Space Station, or launch stowed satellite on an Atlas H to a 240 nm orbit.
2.	OMV retrieves satellite and returns with it to Space Station.
3.	MRMS transfers satellite to storage area.
4.	Attach power and data lines to satellite
5.	EVA astronauts perform physical inspection.
6.	Deploy antennas and solar arrays on satellite.
7.	Perform subsystem and system level tests.
8.	Perform rf testing.
9.	Mate satellite to OTV payload adapter.
10.	Transport satellite to fueling depot via OMV.
11.	Fuel satellite and perform propellant leak tests.
12.	Mate satellite with OTV.
13.	OMV transports the OTV plus satellite out of Space Station control zone.
14.	OTV transports satellite to GEO
15.	Satellite is deployed in GEO from OTV.
16.	OTV performs de-orbit and aerobraking maneuvers.
17.	OMV rendezvous and returns OTV to Space Station.

Table V–12: Launch Scenario for the Closed Architecture Satellite

patible fixture on the spacecraft. The OMV then performs the delta velocity and phasing maneuvers necessary to transport the spacecraft to the Space Station. Once the OMV arrives at the Space Station, it docks and the payload is removed from the OMV and transported to the CSC by the MRMS.

3.2.2 Deployment and Test Operations

Once in the CSC at the Space Station, the spacecraft is attached to a mechanical interface by the MRMS. The umbilicals connecting the satellite to the Space Station power and data management systems are made by the FTS. A physical inspection of the spacecraft is performed by astronauts inside the pressurized module using the video system on the FTS. Any damage or physical defects in the spacecraft is corrected either by extra-vehicular activity by the astronauts or remotely with the FTS.

After the vehicle checks out satisfactorily, power is supplied to the vehicle and its central electronics subsystem (CES) and the TT&C subsystems activated. The CES and TT&C subsystems are required to provide verification of deployment of the C and Ku-band antennas and solar arrays. The payload antennas and solar arrays are then deployed by the FTS as shown in Figure V–15. The deployment operations are controlled and monitored by astronauts in the pressurized module. Telemetry from the spacecraft is also provided to a ground operations center for analysis and verification.

Following verification of deployment, subsystem level checkout of the satellite is performed. Test inputs are supplied to the satellite through the Space Station data management system. The response of the subsystems to the stimuli is monitored by Space Station and ground operations center personnel. If a failure is detected, it is repaired at this time. If the failure requires replacement of a component, the entire subsystem module is replaced.

Due to space limitations, it is unlikely that replacement components are stored at the Space Station. A supply of replacement ORUs should be maintained on the ground ready for launch on the next available flight. The satellites are stored in the CSC until the replacement part arrives. Once the spare part has arrived, the repair

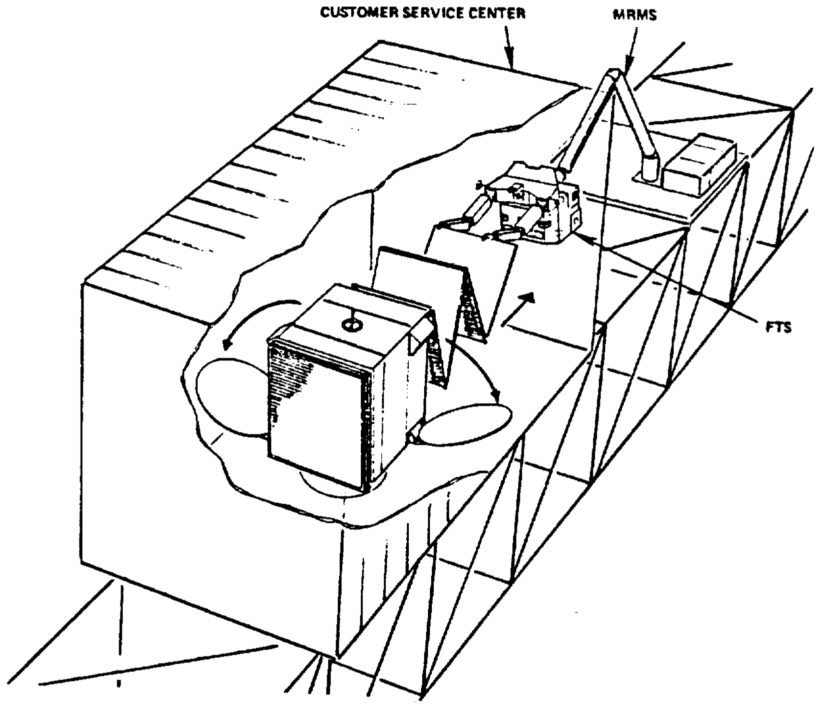


Figure V–15: Deployment of Spacecraft Appendages by the Flight Telerobotic System

is performed by the FTS under astronaut supervision. After all repairs have been completed, the satellite subsystem level tests are repeated.

Following the checkout of the bus and payload subsystems, the spacecraft is transported by the MRMS to a test facility for verification of payload and TT&C performance characteristics. The rf testing is monitored by ground and Space Station personnel. If any failures are detected, the satellite is returned to the CSC for storage and/or repairs.

Once the satellite has been satisfactorily tested, the MRMS transports it to a storage area inside the CSC. The satellite is connected to the power and data management systems and is placed in a storage mode until the subsequent assembly of other spacecraft and/or OTV prelaunch checks have been completed.

3.2.3 Launch Operations

The space-based OTV can place up to 13,680 kg of payload into GEO (Martin Marietta Phase A Study). This means that up to six of the closed architecture spacecraft can be launched on one OTV flight. It is unlikely that the mission would be dedicated to a single satellite and therefore the scenario has been developed for a dual spacecraft launch. Each spacecraft is charged one half of the OTV launch charges.

3.2.3.1 Operations at the Space Station. The launch operations begin with the attachment of the spacecraft to the OTV payload adapter. The payload adapter provides mechanical, electrical, and data interfaces between the OTV and the spacecraft. The MRMS attaches the payload adapter to a surrogate OTV interface that is attached to the Space Station keel structure. After the adapter has been attached, the MRMS retrieves the first spacecraft from the CSC storage area. The spacecraft is attached to the payload adapter by EVA astronauts and/or the FTS. This procedure is repeated until all spacecraft have been attached. A final inspection of the entire assembly is performed by EVA astronauts, and the spacecraft telemetry is monitored by the ground operations center. The attachment oper-

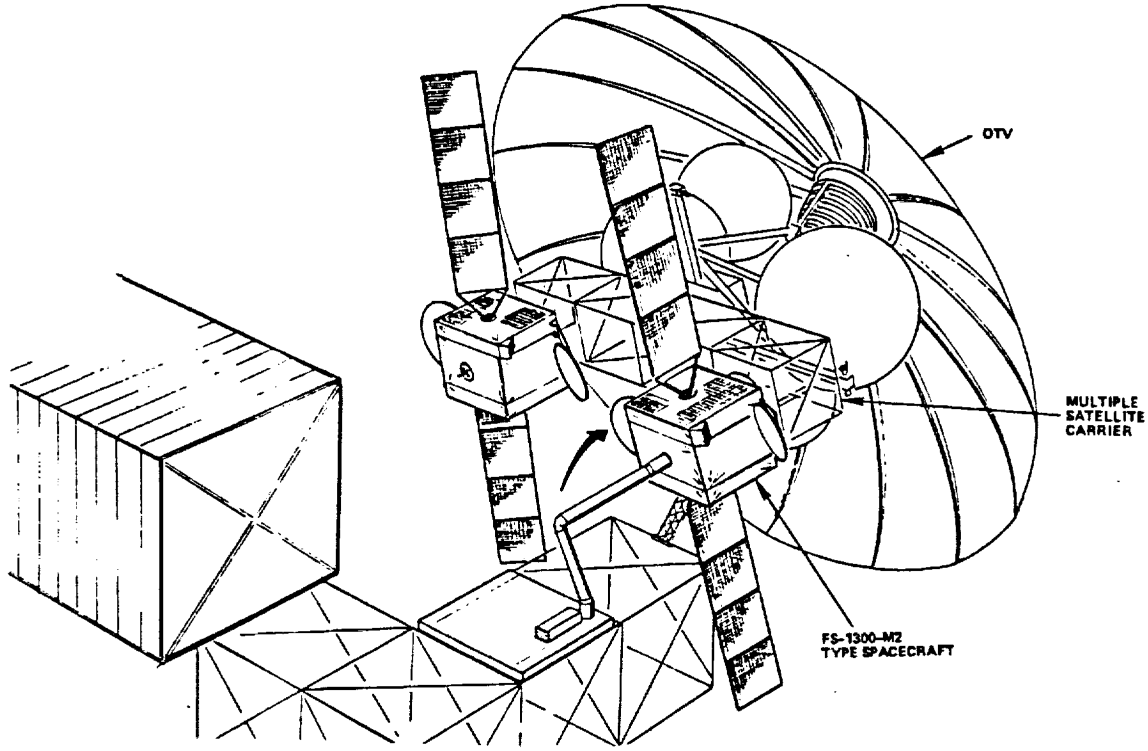


Figure V–16: Attachment of Satellite to the OTV via a Payload Adapter

ation is shown in Figure V–16.

After both spacecraft have been mated to the payload carrier, the entire assembly is inspected by EVA astronauts. Following the inspection, the MRMS grapples the payload carrier and positions it for mating to the OMV. The connections to the OMV are made by EVA astronauts and/or the FTS. Once the connections are made and verified, the OMV transports the payload carrier to the fueling depot. The OMV uses cold gas jets in the vicinity of any Space Station structure, but elsewhere it uses monopropellant thrusters.

3.2.3.2 Fueling Operations. After the OMV has docked to the fuel depot, the fueling umbilical line is connected to the first spacecraft. Since refueling is a potentially hazardous operation, it is recommended that the entire operation be automated. This requires either that the fueling facility have its own dedicated robotics or that the OMV transport the FTS to the facility. After the umbilical connections are verified, the fluid transfer proceeds under control of Space Station and ground operations center personnel. Before the fueling umbilicals are removed, propellant leak tests are performed to verify the integrity of the propellant plumbing and valves. Following the leak test, the umbilical lines are disconnected and attached to the next satellite. This procedure is repeated until all spacecraft are fueled.

3.2.3.3 OTV Launch Operations. Upon completion of the satellite fueling operation, the OMV transports the payload adapter to the OTV staging area. The MRMS is used to demate the adapter from the OMV and to position it for attachment to the OTV. The mechanical, power, and data connections to the OTV are made by EVA astronauts and/or the FTS. Once all the connections have been made, the entire assembly is inspected by EVA astronauts and system level checks are made by the crews inside the Space Station and in the ground operations center.

After all checks are completed, the OMV is mated to the OTV. The OMV then moves the OTV away from the Space Station using its cold gas thrusters. Once clear of the Space Station and the free flying platforms, the OMV uses its monopropellant thrusters to move the OTV outside the Space Station Control Zone. The OMV then separates from the OTV and returns to the Space Station.

After OMV separation, the OTV receives an ephemeris update from the Global Positioning System (GPS) satellites and orientates itself for the first burn for injection in Geostationary Transfer Orbit (GTO). The OTV performs inclination and circularization burns for insertion into an equatorial, geostationary orbit. It is also possible to place the spacecraft in a slightly subsynchronous orbit, giving it a slight eastward drift. This results in a slight propellant savings provided the orbit injection are optimized so that none of the satellites require a westward drift. Detailed mission analysis of the deployment of the spacecraft is beyond the scope of this study. The OTV deploys the satellites individually and provides adequate separation between satellites to prevent collisions.

3.2.3.4 OTV Return to Space Station.

After the last satellite is deployed, the OTV performs a de-orbit burn to place it in the proper aerobraking trajectory. During the aerobraking maneuver, the OTV not only reduces the apogee of its orbit but also performs a plane change to a 28.5° inclination. Use of aerodynamic forces to reduce the apogee and perform the plane change results in a substantial fuel savings. After exiting from the aerobraking corridor, the OTV performs orbit raising and circularization burns necessary for rendezvous with the Space Station. The SB-OMV is used to retrieve the OTV and return it the processing area.

3.2.4 Time/Costs for Mission

A mission timeline for the OTV launch is shown in Table V–14. It is estimated to take 169 hr Internal Vehicular Activity (IVA) and 2 hr External Vehicular Activity (EVA) of Space Station crew time to deploy, test and launch the satellite. The launch costs and crew hours are shown in Tables V–13 and V–15, respectively. (The transportation cost to the Space Station is based on use of the American Rocket ILV at $4,400/kg.)

Capital Expenditure Item	Cost ($M)
Satellite	64.8
Transportation to Space Station	8.0
Launch support	1.6
OTV fuel	26.5
Space Station charges	3.0
OMV/OTV fees	6.1
Mission operations	2.6
Insurance (11%)	13.7
Total	126.3

Table V–13: Launch Costs (Closed Design)

3.3 Open Architecture Configuration

The open architecture configuration (also known as the FS-1300 M2) presented in Subsection V-2.3 is designed to allow subsystem level assembly, deployment, and test at the Space Station. This design enables the individual components to be transported to the Space Station over several different launches. The components can then be assembled and the complete spacecraft tested by the Space Station crew. The vehicle is placed into GEO by the OTV. The complete scenario for the Space Station operations is shown in Table V–16 and is described below.

3.3.1 Transportation to Space Station

The decision to fully integrate the payload and bus subsystem modules on the ground prior to launch is primarily made from a reliability standpoint. Secondary considerations are the level of effort and support required to perform these tasks at the Space Station.

Figure V–17 depicts the decision tree associated with the level of integration to be performed at the Space Station. The various options considered ranged from no preliminary assembly to assembly and test of subsystem modules on the ground. Launch of individual components represents the largest program cost option, in spite

Time (hr)	Mission Event
T_0	OMV moves OTV out of Space Station control zone.
+2.2	First perigee burn by OTV.
+4.0	Second perigee burn by OTV.
+6.8	Third perigee burn by OTV.
+12.8	Fourth perigee burn by OTV.
+16.9	Apogee burn by OTV.
+41.3	Trim burn by OTV.
+43.8	Deploy first satellite from OTV.
+45.8	OTV performs east-west separation maneuver.
+55.8	Deploy second satellite from OTV.
+60.6	OTV performs de-orbit & aerobraking maneuvers.
+60.9	OTV performs orbit raising maneuvers to 240 nm.
+62.9	OMV transfers OTV to Space Station docking area.
+63.9	MRMS grapples OTV and docks to Station.

Table V–14: Mission Timeline for OTV Launch of Closed Architecture Satellite

Space Station Crew Activity	IVA (hr)	EVA (hr)
Review procedures for cargo off-loading	4	
Remove satellite and transfer to storage	2	
Connect power/data lines to satellite	1	
Inspection and test	60	2
Review deployment checklist	6	
Deploy appendages	10	
Review fueling procedures/checklists	6	
Transfer satellite to fueling port	4	
Fuel satellite	3	
Mate satellite with payload adapter	3	
Launch/recover OTV	50	
Total Crew Time	149	2

Table V–15: Space Station Crew Time – Closed Architecture Satellite

1.	Launch satellite components on shared Shuttle flight(s) to Space Station, and/or launch satellite components on expendable booster(s) to a 240 nm orbit.
2.	OMV retrieves booster payload and returns with it to Space Station.
3.	MRMS transfers components to storage area.
4.	Components are stored in controlled environment until assembly.
5.	Attach power and data lines to subsystem modules.
6.	EVA Space Station astronauts perform physical inspection of components.
7.	Subsystem level tests of modules are performed.
8.	Assemble truss structure.
9.	Assemble propulsion subsystem.
10.	Attach harness and electrical connectors to structure.
11.	Attach module and antenna interfaces to structure.
12.	Attach thermal blankets to truss structure.
13.	Attach modules and antennas to truss structure.
14.	Install solar arrays.
15.	Perform subsystem and system level tests.
16.	Perform rf testing.
17.	Mate satellite to OTV payload adapter.
18.	Transport satellite to fueling depot via OMV.
19.	Fuel satellite and perform propellant leak tests.
20.	Mate with OTV.
21.	OMV transports OTV plus satellite out of Space Station control zone.
22.	OTV transports satellite to GEO.
23.	Satellite deployed in GEO by OTV.
24.	OTV performs de-orbit and aerobraking maneuvers.
25.	OMV rendezvous and returns OTV to Space Station.

Table V–16: Assembly/Launch Scenario for Open Architecture Satellite

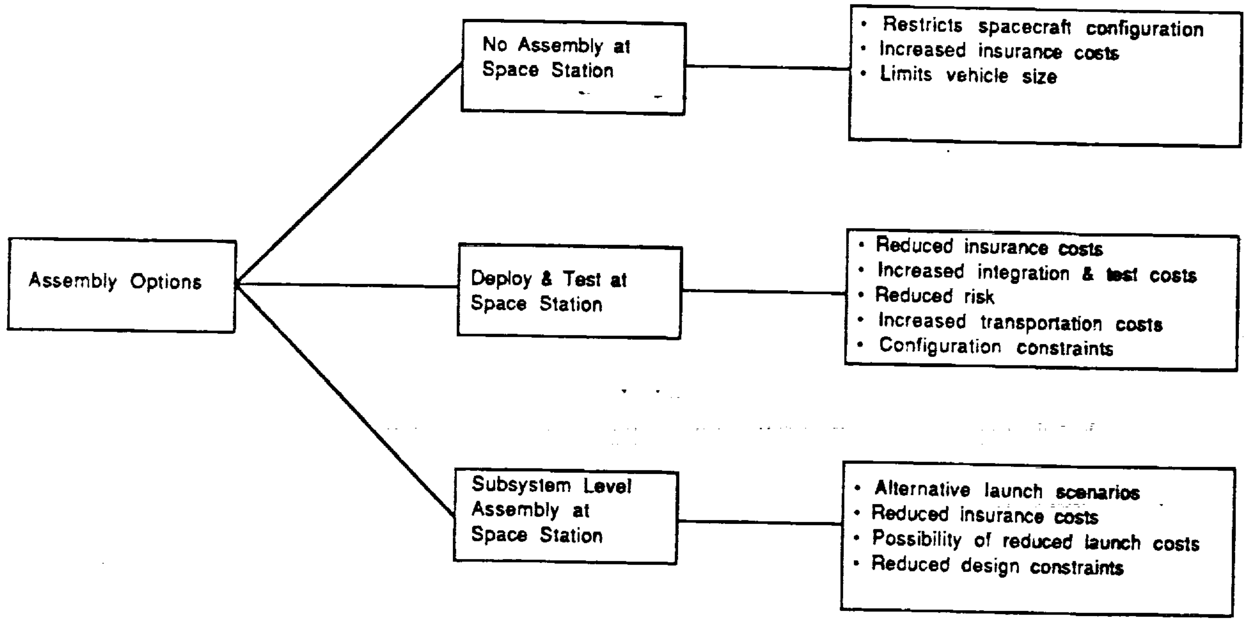


Figure V–17: Level of Integration Decision Tree

of the fact that it results in the lowest launch charges.

A typical spacecraft is tested end-to-end on the ground to ensure that system level performance requirements are met. This results in either:

i. Completely integrating the spacecraft on the ground, disassembling it for launch, and integrating it again at the Space Station, or

ii. Unit level checkout on the ground and system level integration and test at the Space Station.

The latter option is most cost effective since it reduces the amount of test and integration. Thus the spacecraft is launched as completely integrated and tested modules. The modules can be transported to the Space Station over several launches and assembled by astronaut and/or the FTS. This decision opens up the possibility of new transportation scenarios where components are manifested on launch vehicles on a space available basis. The spacecraft components are unloaded from their launch vehicle and stored in the CSC as described in Subsection V-3.2.1. The components remain in storage until the all pieces of the spacecraft are transported to the Station.

A pricing policy could be developed to encourage users to spread the transportation of a spacecraft to the Space Station over several launches. This in turn would encourage complete utilization of available launch throw weight and fairing volume. This scenario is attractive from an insurance standpoint as it distributes the risk over several launches and minimizes the potential loss on any single launch.

3.3.2 Assembly Operations

As the spacecraft components arrive at the Space Station, they are transported to the storage facility and placed in a storage rack by the MRMS. Power and data lines are connected by the FTS or EVA astronaut. After the all the connections are made, the module undergoes system level tests. The tests are performed by the crew inside the pressurized module and are monitored on the earth. If a failure is detected in a subsystem module, the module is returned to the ground for repair and a replacement sent up to the Station. This procedure is repeated for all subsystem modules. A similar procedure is followed for the structure and antennas except they are not tested at the Space Station.

The assembly operations begin after all modules are received and tested. The first operation is to attach the truss structure to the central cylinder. The center truss assembly is attached to a surrogate OTV interface by the MRMS. The truss structure is then attached by the FTS or EVA astronaut. Once the truss is assembled, the propulsion system is installed. This entails connecting the propellant lines to the valves, tanks, and thrusters and attaching the lines, valves and thrusters to the truss structure. This operation is performed most effectively by EVA astronauts. The truss assembly operation is shown in Figure V–18

After the propulsion system is installed, the remaining interface hardware, waveguides, and harness is assembled and attached to the truss structure. This operation is performed by EVA astronauts with some assistance from the FTS. Once this operation is complete, the thermal blankets are attached to the truss structure by EVA astronauts.

The next step in the assembly is the installation of the solar arrays. The Solar Array Drive Assemblies (SADAs) are attached to the truss structure by EVA astronauts. The solar array masts are then deployed and moved into position for assembly by the FTS. The final connection to the SADAs is performed by EVA astronauts.

The final assembly step is to attach the antenna, payload, and house keeping modules. This operation is performed by the FTS using a special module interface tool. The FTS removes the modules from the storage rack and inserts them into the spacecraft/module interface. Once the module is inserted into the interface, it is locked into position using the interface tool. This procedure is repeated until all of the modules are attached. The module installation operation is shown in Figure V–19

At this point the assembly operations are complete and the FTS returns the tools and other assembly equipment to the appropriate storage locations. The next operations are the deployment of the solar array panels, system level testing, fueling, and mating with the payload adapter. These operations are described in Subsection V-3.2.2.

Capital Expenditure Item	Cost ($M)
Satellite	69.4
Transportation to Space Station	8.0
Launch support	1.6
OTV fuel	26.7
Space Station charges	3.0
OMV/OTV fees	6.1
Mission operations	2.6
Insurance (11%)	14.4
Total	133.9

Table V–17: Launch Costs (Open Design)

3.3.3 Launch Operations

The open architecture configuration uses an OTV launch and the launch operations are similar to those described in Section V-3.2.3 for the closed architecture configuration.

3.3.4 Time/Costs for Mission

A mission timeline for the OTV launch is the same as shown in Table V–14 for the closed architecture satellite. However, IVA and EVA times are longer – it is estimated to take 169 hr of EVA and 46 hr of IVA crew time to assemble and launch a single satellite. The estimated cost involved in these processes is $134 M. The launch costs are given in Table V–17, and the Space Station crew hours are shown in Table V–18.

4 Servicing Scenarios

The baseline business-as-usual satellite described in Subsection V-1.2 does not have any provisions for on-orbit servicing. A program lifetime of 24 years is achieved by launching a replacement satellite after the initial 12 year lifetime is complete.

For purposes of comparison, the study assumes a constellation of two satellites placed at 84° W and 144° W longitude. This assumption is made for the three scenarios discussed in this subsection. since the satellites have a 12 year design

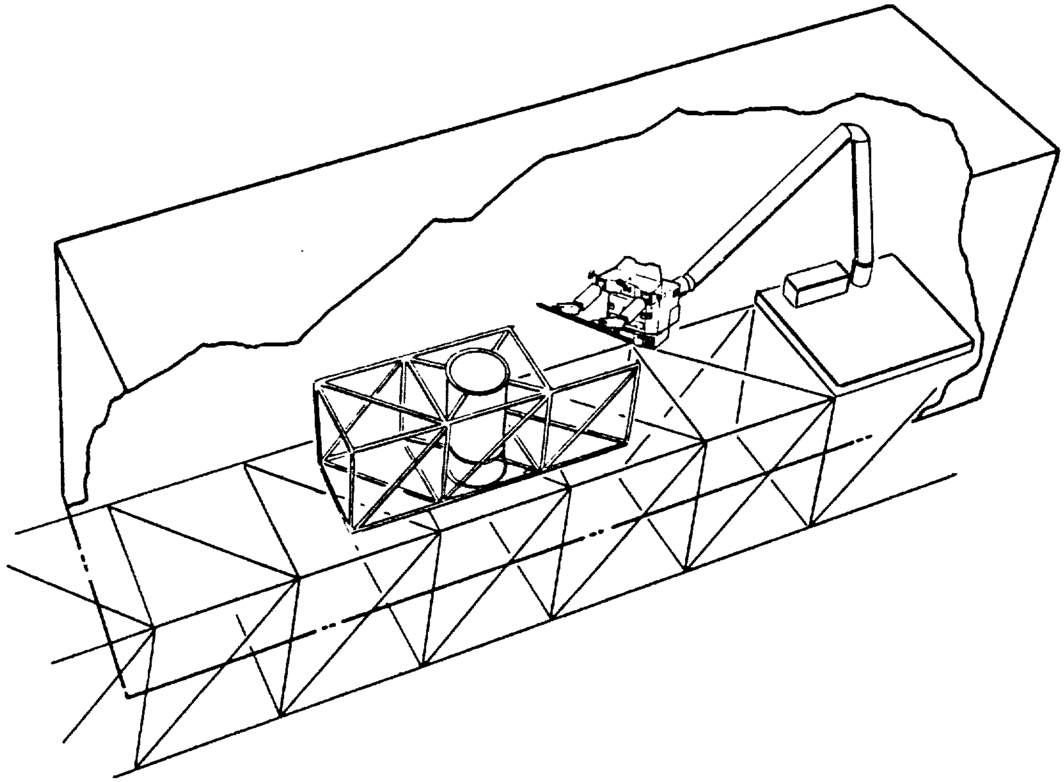


Figure V–18: Truss Assembly Operation

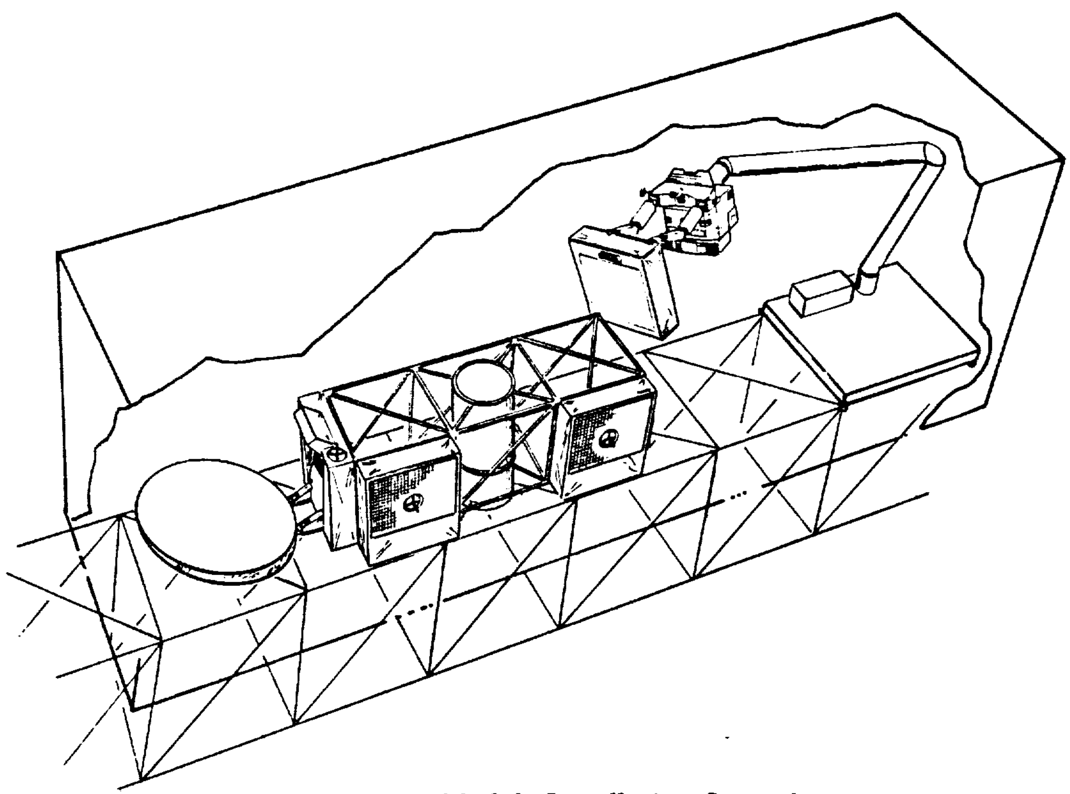


Figure V–19: Module Installation Operation

Space Station Crew Activity	IVA (hr)	EVA (hr)
Review procedures for cargo off-loading	12	
Remove satellite and transfer to storage	8	
Connect power/data lines to satellite	2	
Inspection and test	80	12
Review assembly/deployment checklist	30	
Assembly operations	21	34
Deploy appendages	1	
Review fueling procedures/checklists	6	
Transfer satellite to fueling port	4	
Fuel satellite	3	
Mate satellite with payload adapter	3	
Launch/recover OTV	50	
Total Crew Time	169	46

Table V–18: Space Station Crew Time - Assembly/Launch of Open Architecture Satellite

life, the replacement satellites are launched during year 12, and the original satellites are boosted into supersynchronous orbit at the end of year 12.

4.1 Scenario for Refuelable Design

The modified baseline design has sufficient fuel for 8 years of normal operation. A refueling mission is scheduled during the third quarter of year 7. It is assumed that the refueling mission is combined with other servicing, retrieval or launch operations and that the mission costs are divided among the users according to payload mass. In addition, it is assumed that two satellites are fueled during the same mission. The operational flow of the refueling scenario is shown in Figure V–20.

4.1.1 Operations at the Space Station

The fueling mission begins at the Space Station with the integration of the fueling kit, remote servicer, OMV with the OTV. This operation is performed with the MRMS and/or EVA astronauts. The assembly is inspected by EVA astronauts and system checks performed by IVA astronauts. The entire assembly is then transferred to the fueling depot by the OMV. Two options exist for transporting the fuel to GEO:

i. A dedicated fueling kit with sufficient capacity to refuel several satellites is used, or

ii. If the extended range version of the OMV is used, the propellant can be scavenged from the bipropellant propulsion module.

The latter option is being investigated by NASA/MSFC. However, it is unlikely that the OMV propulsion module would be used for a GEO servicing mission. The OTV would be used to provide the thrust for large propulsive maneuvers, and therefore the OMV would not require the added propulsion capability provided by the bipropellant module. In addition, the empty bipropellant module adds 760 kg of mass to the OMV, which is much greater than the dedicated fueling kit.

Based on this reasoning, it is decided to use the dedicated fueling kit. The equipment required for the servicing operation and their respective masses are shown in Table V–19.

4.1.2 Transport from Station to GEO

Once the fueling of the OMV, OTV, fueling kit, and any other payload requiring fuel is complete, the OMV cold gas thrusters are used to move away from the fuel depot. Once clear of all critical structures, the OMV monopropellant system

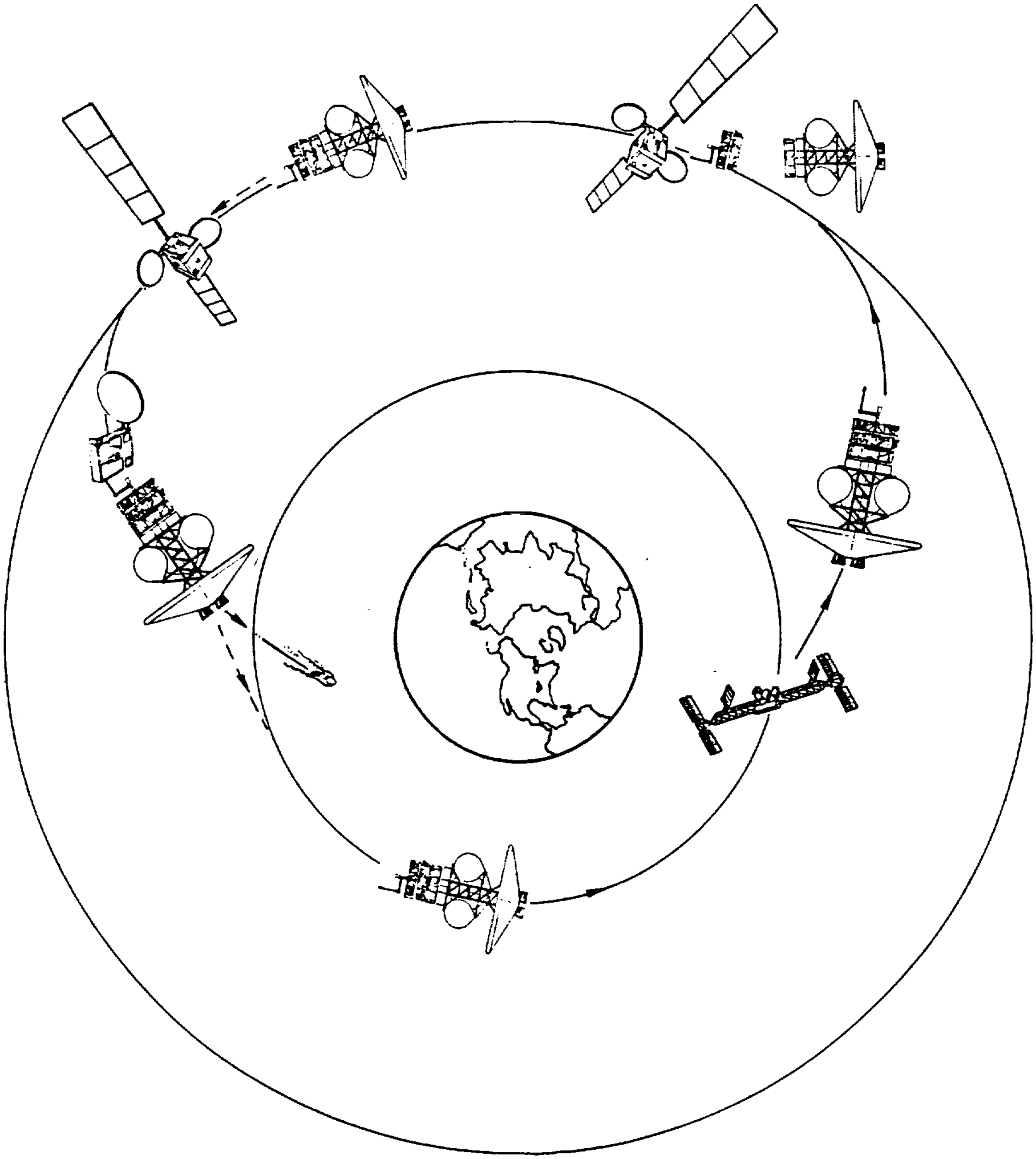


Figure V–20: Operational Flow of GEO Refueling Mission

Mission Equipment/Fuel	Mass (kg)
OTV	3,734
OMV (small version)	1,675
IOSS	286
Fueling Kit	230
Total	5,925
MMH fuel	68
NTO fuel	112
Total equip. + fuel	6,105

Table V–19: Refueling Mission Mass

moves the OTV outside the control zone and into position for the first perigee burn. The OTV performs the necessary perigee, inclination, and apogee maneuvers to place the OMV in GEO.

The OTV also performs the large east-west maneuvers necessary to rendezvous with the satellites to be serviced. In order to minimize the time and fuel required by these east-west maneuvers, the mission should be scheduled so that the maximum separation between satellites is less than 90°. For larger satellite separations, the satellites should be moved closer together by performing east-west maneuvers prior to the servicing mission. This is to be avoided because of the additional revenue loss due to the increased satellite down time.

4.1.3 Operations in GEO

Once the OTV is placed into geostationary orbit, it performs the east-west maneuvers required to move to the orbital slots containing the satellites to be serviced. During the launch, rendezvous and de-orbit phases of the mission, the OTV receives ephemeris updates from the Global Positioning System (GPS) and tracking data from the ground. The OTV uses tracking data from the satellite for initial rendezvous operations. The final rendezvous operations are performed using the OMV radar and TV cameras. The communication interfaces required to support the servicing mission are shown in Figure V–21.

When the OTV moves within 3 km of the satellite, the OMV separates and moves toward the satellite under automatic control. When the satellite/OMV separation is approximately 300 m, the satellite is visible with the OMV video cameras. Once visual contact has been made, the OMV is switched to ground control and an operator performs the final rendezvous and docking operations under manual control.

During the final docking maneuvers, the OMV cold gas system is used to avoid contamination of sensitive surfaces. Prior to final docking, the satellite's propulsion and attitude control subsystems are shut down to prevent control difficulties or plume impingements. The OMV maintains attitude control for both vehicles during the servicing operation, eliminating the need for control system interfaces between the two vehicles.

Once the satellite attitude control system is shut down, the servicer arm removes the fueling umbilical from the umbilical storage rack and attaches it to the satellite fueling port, as shown in Figure V–22. Connectors are used that allow both the monomethylhydrazine (MMH) and nitrogen tetraoxide (NTO) to be replenished with a single connection. These connectors are self-aligning and are self-latching. Once the connections have been verified, the inhibit valves open and the fluid transfer begins. The fluid transfer operation is monitored by the operations center on the ground.

Upon verification that the proper amount of fuel is transferred, the inhibit valves are closed and the connector purged. The servicer removes the umbilical and returns it to the storage rack. The OMV then demates from the satellite and backs away using its cold gas thrusters.

Once the OMV has backed away, the satellite attitude control and propulsion subsystems are re-enabled. The disturbances due to the OMV separation may impart a slight rotation rate about one or more of the satellite axes, but these rotation rates should be well within the control capacity of the satellite control system. The attitude rates should be damped out and the satellite returned to normal mode within 1 hour after OMV separation. Under normal circumstances, no special station keeping maneuvers are required due to the disturbances of the

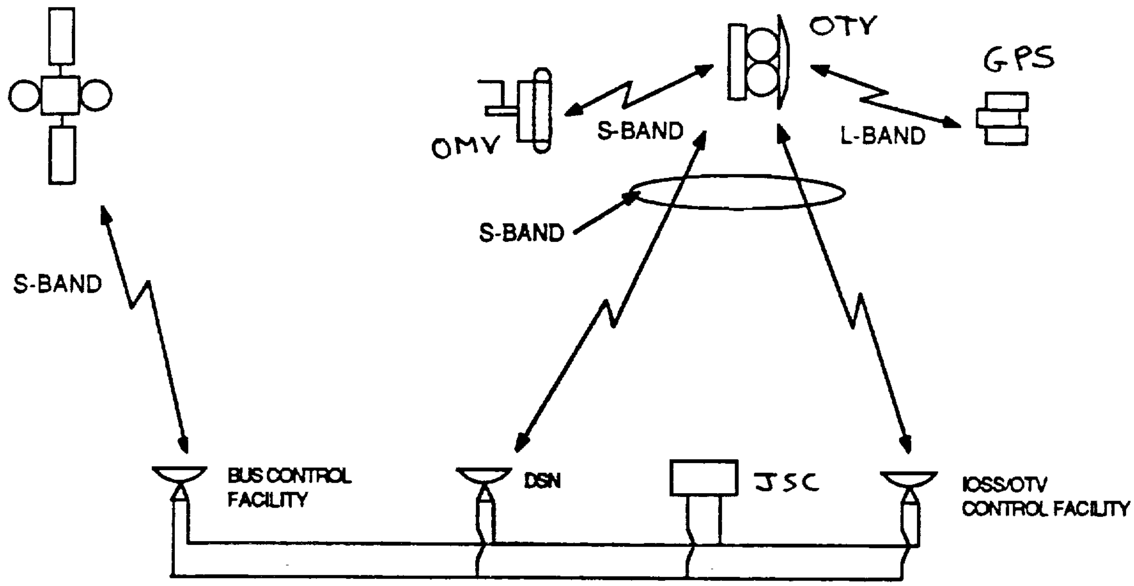


Figure V–21: Servicing Mission Communication Interfaces

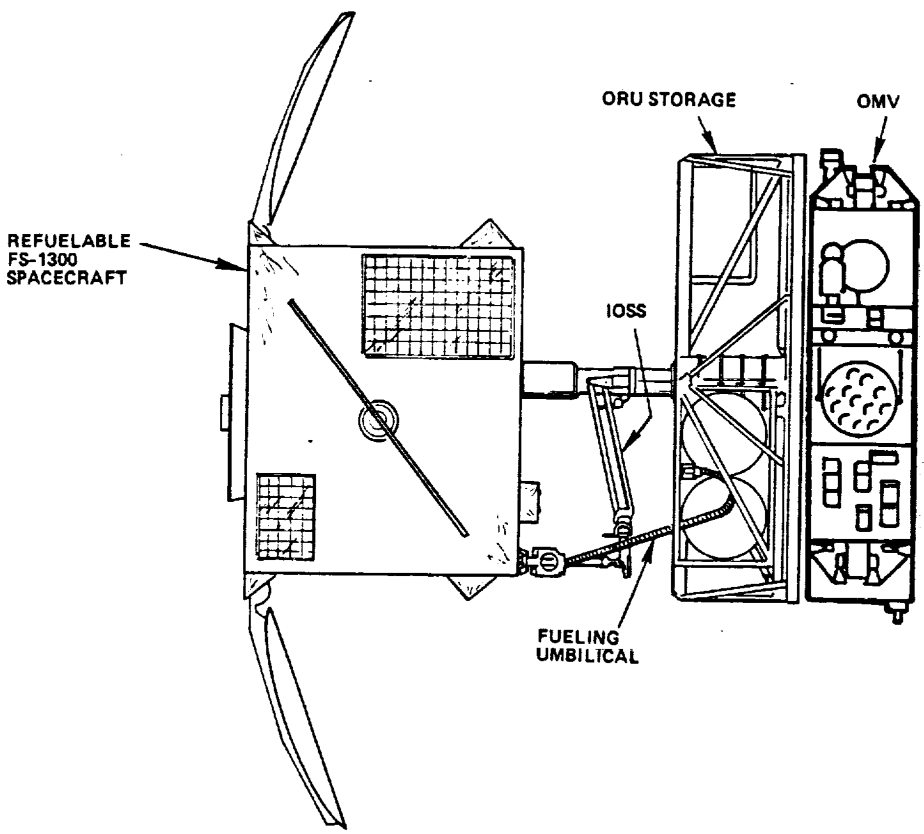


Figure V–22: Fueling Umbilical Connection servicing operations.

The OMV returns to the OTV, docks, and performs an east-west maneuver to rendezvous with the next spacecraft to be serviced. This cycle is repeated until the servicing schedule is complete. At that point the OTV performs the de-orbit and aerobraking maneuvers necessary to return the OMV and servicing equipment to the Space Station. The OMV is used for the final docking operations at the Space Station. A mission timeline for the GEO satellite refueling mission is shown in Table V–20.

4.2 Scenario for Closed Design

The closed architecture satellite is designed to allow refueling and replacement of all life-limited housekeeping and payload equipment with the exception of the solar arrays. The ability to service provides a mechanism for restoring the satellite to its initial capacity without incurring the costs of launching an entirely new spacecraft. The subsystems that are completely or partially replaced are shown in Table V–21.

The scenario assumes that two satellites located as 84° W and 144° W are serviced on the same mission. The servicing scenarios for both the closed and open architecture satellites are developed for scheduled servicing missions. These scenarios also apply in the case of emergency repair of a failed satellite.

Emergency repair is a viable option only when combined with other servicing/repair operations or a satellite launch. The cost of transporting the servicing equipment to GEO is prohibitive for servicing "on demand". The overall operational flow of the mission is shown in Figure V–23 and is described in the following discussion.

4.2.1 Operations at the Space Station

The replacement components described above may be transported to the Space Station via either the shuttle or an expendable launch vehicle. The replacement components are received and transported to the CSC using the same procedures described in Subsection V-3.1.1. Once inside the CSC, the modules are placed into an ORU rack compatible with the OMV and IOSS. Power and data lines are connected to the modules for monitoring and thermal control purposes. Prior to the servicing mission each of the modules undergoes subsystem level tests. If a failure is detected, a spare is launched on the next available flight and the failed module is returned to the ground for repair.

Once all the modules have been checked out, the power and data lines are removed and the MRMS positions the ORU rack for integration with the OMV. The integration of the remote servicer, the ORU rack with the OMV is performed by EVA astronauts and/or the FTS. Once the integration operations have been complete, the OMV is positioned by the MRMS for integration with the OTV. Again, the integration operation is carried out by EVA astronauts and/or the FTS. The servicing equipment required and their respective masses are shown in Table V–22. Once the OMV and OTV have been integrated, system level tests are performed by a crew inside the pressurized module.

Following the checkout of the servicing systems, the OMV transfers the system to the fueling depot. The fueling operation is carried out as described in Subsection V-3.1.3. Once the OMV, fueling kit and OTV have been fueled, the OMV moves the system outside the Space Station control zone.

4.2.2 Transport, Rendezvous, Docking

The OTV transports its cargo to GEO orbit. The orbit insertion and initial OMV rendezvous operations are identical to those described in Subsection V-4.1. The only minor difference in the rendezvous and docking operations is that prior to docking, the OMV performs a fly-by inspection under ground control. The purpose of the inspection is to determine if any damage has occurred to the satellite that might affect the servicing operations.

Following the inspection, the satellite attitude control and propulsion is safed to prevent control difficulties during the servicing operation. Once the satellite has been safed, the OMV docks with the satellite. The docking operations are expected to impart some minor disturbances to the

Time (hr)	Mission Event
T_0	OMV moves OTV out of Space Station Control zone.
+2.2	First perigee burn by OTV.
+4.0	Second perigee burn by OTV.
+6.8	Third perigee burn by OTV.
+12.8	Fourth perigee burn by OTV.
+16.9	Apogee burn by OTV.
+41.3	Trim burn and rendezvous with 84° satellite by OTV.
+42.8	OMV separates from OTV.
+44.8	OMV rendezvous and docks with satellite.
+45.8	Refueling operations for first GEO satellite.
+49.8	OMV demates from satellite.
+51.8	OMV docks with OTV.
+57.8	OTV performs east-west maneuver.
+71.8	OTV rendezvous with satellite at 144 ° W.
+73.3	OMV separates from OTV.
+75.3	OMV rendezvous and docks with satellite.
+76.3	Refueling operations for second GEO satellite.
+80.3	OMV demates from satellite.
+86.3	OTV performs de-orbit & aerobraking maneuvers.
+92.6	OTV performs orbit raising maneuvers to 240 nm.
+94.6	OMV transfers OTV to Space Station docking area.
+95.6	MRMS grapples OTV and docks to Station.

Table V-20: Mission Timeline for GEO Satellite Refueling Mission

Subsystem	Servicing Capacity	Replacement Mass (kg)
Attitude Control	Replace all subsystem components.	64
Propulsion	Refueling.	421
Electrical Power	Replace all subsystem components except solar arrays and shunt regulators.	107
TT&C	Replace all subsystem components.	10
Control Electronics	Replace all subsystem components.	51
Thermal Control	Replace blankets, heaters and radiators associated with subsystem modules.	26
Structure	Replace module structure.	140
Payload	Replace all subsystem components except antennas and feeds.	405
Total (replaced)		1,224

Table V-21: Mass Replaced During GEO Servicing of Closed Architecture Satellite

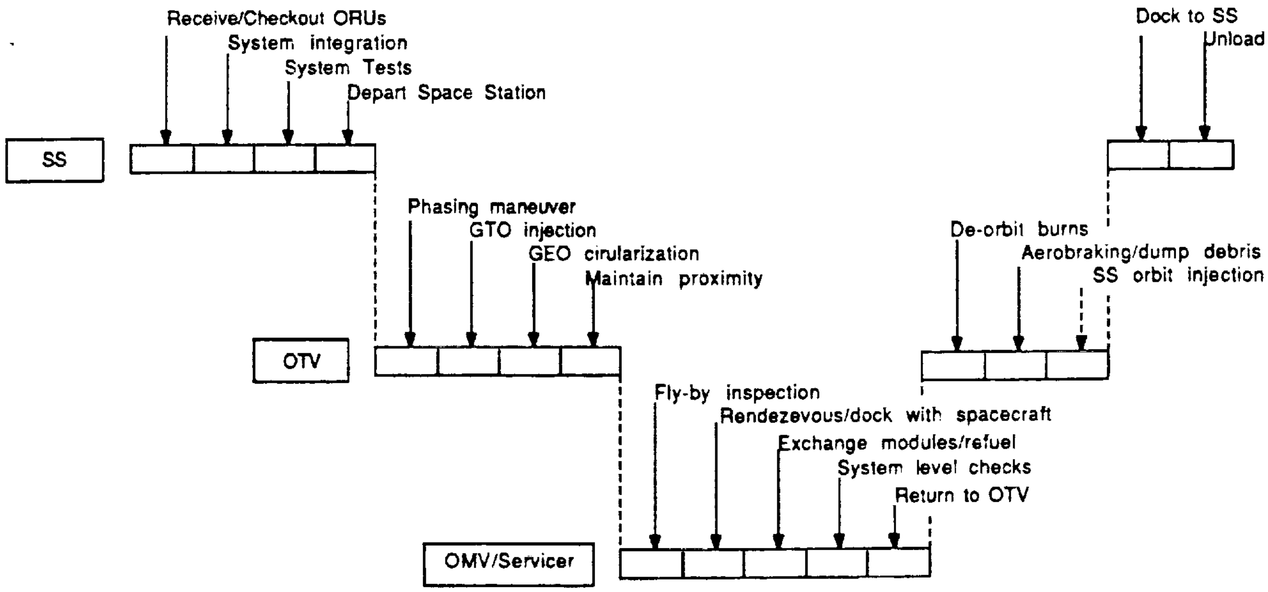


Figure V–23: Flow of Operations During Servicing of Satellite

satellite, the largest of which will be a negative delta velocity along the radius of the orbit. The magnitude of this delta velocity should be less than 6 cm/s and therefore should have only a minor effect on the satellite orbit.

4.2.3 GEO Servicing Operations

Once the OMV is hard docked, the housekeeping and payload subsystems are shut down to prevent damage during module replacement. Assuming the IOSS is used as the robotic servicer, the module exchange involves the following operations:

i. Remove the old module from the satellite.

ii. Invert the module for insertion into the ORU rack on the OMV.

iii. Transport the module to a vacant location in the ORU rack.

iv. Insert the module into the ORU rack.

v. Locate the replacement module in the ORU rack.

vi. Remove the new module from the ORU rack.

vii. Invert it for insertion into the satellite.

viii. Transport it to the vacated location on the satellite.

ix. Insert the new module into the satellite.

The trajectories and moves for each module exchange operation are preprogrammed and executed under ground operator supervision. The module exchange sequence takes about 10 minutes per module. Therefore it takes approximately 40 minutes to replace the C-band, Ku-band, battery, and housekeeping modules. If a change to the satellite configuration has occurred or any difficulty arises in the real-time execution, the operator interrupts the automated sequence and continues under manual control until the difficulty has been resolved. The module exchange operation is shown in Figure V-2.

Once the entire complement of modules is exchanged, the satellite is refueled using the same procedure described in Subsection V-4.1. Following the refueling operation, power is restored to the payload and bus subsystems, and system level tests are performed by the ground operators. If a failure is detected, a diagnosis of the

Mission Equipment/Fuel	Mass (kg)
OTV	3,734
OMV (small version)	1,675
IOSS	286
Fueling Kit	230
Total	5,925
MMH fuel	159
NTO fuel	262
Module mass	803
Total equip. + fuel	7,149

Table V–22: Servicing Mass (Closed Design)

Capital Expenditure Item	Cost ($M)
Replacement components	36.1
Transportation	24.6
Launch support	3.2
Mission operations	4.8
OMV/OTV use fees	6.1
Space Station fees	3.3
Insurance	12.1
Total	90.2

Table V–23: Servicing Cost (Closed Design)

problem is made. Since the modules are not designed for remote repair, repair activities are limited to removing and re-inserting the module to verify the power and data connections. If the failure persists a decision must be made about its operational impact. If the failure prevents operation, the original module (or possibly the spare for the second satellite) could be returned to service until another servicing mission can be scheduled.

Once all servicing operations are complete, the OMV separates from the spacecraft and returns to the OTV. Immediately after OMV separation, the satellite propulsion and attitude control subsystems are re-enabled and the satellite is returned to a normal mode of operation. The impact of the servicing operation on the satellite should be minimal, and the resulting attitude rates can be damped out within 30 minutes after the departure of the OMV. Normal operations should be resumed shortly thereafter. The total outage time due to servicing is approximately 12 hours.

After the OMV has docked to the OTV, the OTV performs an east-west maneuver to move from 84° W to the satellite stationed at 144° W. The transit time to the next satellite is approximately two days using a negative delta velocity of 14.6 m/s. Once the OTV arrives on station, the servicing operations described above are repeated.

After the servicing operations have been completed and the OMV has docked to the OTV, the OTV returns the OMV, servicer and spent ORUs to low earth orbit. The operations for de-orbit and return to the Space Station are identical to those described in Subsection V-4.1. The mission cost data is shown in Table V–23. A timeline for the servicing mission is shown in Table V–26.

4.2.4 Disposal of Spent ORUs

There is an issue about the disposal of the spent Orbital Replacement Units (ORUs) after servicing operations are complete. There are three possible solutions to this problem:

i. Return the modules to earth for engineering analysis and/or refurbishment. There is a significant fuel cost to do so, and the modules are expected to have little salvage value.

ii. Dispose of the modules during the aerobraking maneuver or in low earth orbit immediately following aerobraking. The modules would enter into the atmosphere and be destroyed. This requires a redesign of the planned ORU rack servicer to allow the modules to be ejected without damaging the servicer. Also, care must be taken to ensure that the modules are completely consumed and that debris does not fall to earth.

ii. Create an orbital junk yard in GEO and/or LEO.

There is no clear direction on the disposal of space debris, but action should be taken in this area. It is beyond the scope of this study to perform a detailed analysis of this problem, but future studies should include the above alternatives.

4.3 Scenario for Open Design

The open architecture configuration is similar to the closed architecture configuration in that they are both designed for subsystem level servicing. The only difference between the two configurations is that the open design provides on-orbit storage of degraded/failed ORUs. The replacement masses of the various subsystems and the overall mission mass breakdown are shown in Tables V–24 and V–27 respectively.

The servicing scenario for the open design is identical to the closed design scenario described in Subsection V-4.2 except for a minor change in the module exchange procedure. Instead of removing the ORUs from the satellite and loading them into the ORU rack on the OMV, the modules are relocated to storage locations on the satellite. The housekeeping modules are placed in passive storage locations on the earth facing panels of the $\pm x$ ends of the truss. The replacement payload modules are placed in active locations on the south facing panels of the satellite. The replacement modules could operate in parallel with the existing modules, providing additional traffic capacity or redundancy. The mod-

Mission Equipment	Mass (kg)
OTV	3,734
OMV (small version)	1,675
IOSS	286
Fueling Kit	230
Total	5,925
MMH fuel	259
NTO fuel	457
Module mass	803
Total equip. + fuel	7,444

Table V–24: Servicing Mass (Open Design)

Capital Expenditure Item	Cost ($M)
Replacement components	36.1
Transportation	25.1
Launch support	3.2
Mission operations	5.0
OMV/OTV use fees	6.1
Space Station fees	3.3
Insurance	12.2
Total	91.0

Table V–25: Servicing Cost (Open Design)

Time (hr)	Mission Event
T_0	OMV moves OTV out of Space Station Control zone.
+2.2	First perigee burn by OTV.
+4.0	Second perigee burn by OTV.
+6.8	Third perigee burn by OTV.
+12.8	Fourth perigee burn by OTV.
+16.9	Apogee burn by OTV.
+41.3	Trim burn and rendezvous with 84° satellite by OTV.
+42.8	OMV separates from OTV.
+44.8	OMV rendezvous and docks with satellite.
+45.8	Module replacement and refueling operations for first satellite.
+53.6	System level checkout of first satellite.
+57.2	OMV demates from satellite.
+58.2	OMV docks with OTV.
+64.2	OTV performs east-west maneuver.
+112.2	OTV rendezvous with satellite at 144° W.
+114.2	OMV separates from OTV.
+115.2	OMV rendezvous and docks to satellite.
+116.2	Module replacement and refueling operations for second satellite.
+124.0	System level checkout of second satellite.
+131.8	OMV demates from satellite.
+132.8	OTV performs de-orbit & aerobraking maneuvers.
+139.1	OTV performs orbit raising maneuvers to 240 nm.
+141.1	OMV transfers OTV to Space Station docking area.
+142.1	MRMS grapples OTV and docks to Station.

Table V–26: Mission Timeline – Servicing Mission for Closed Architecture Satellite

Subsystem	Servicing Capacity	Replacement Mass (kg)
Attitude Control	Replace all subsystem components.	72
Propulsion	Refueling.	572
Electrical Power	Replace all subsystem components except solar arrays and shunt regulators.	107
TT&C	Replace all subsystem components.	10
Control Electronics	Replace all subsystem components.	51
Thermal Control	Replace blankets, heaters and radiators associated with subsystem modules.	26
Structure	Replace module structure.	140
Payload	Replace all subsystem components except antennas and feeds.	405
Total		1,383

Table V–27: Mass Replaced During Servicing of Open Architecture Satellite ule relocation/replacement operation is shown in Figure V–24.

In addition to potentially providing additional transponder revenue, storing the modules on the satellite eliminates the need for returning the ORUs to LEO or earth, which translates into a reduction in transportation costs.

The servicing mission cost data is shown in Table V–25, and the servicing mission timeline is shown in Table V–28. The total satellite outage time is approximately 12.5 hours.

5 Economic Analysis

The baseline, refuelable, and modular configurations are analyzed to determine their relative economic performance. In order to accurately access the performance of the serviceable designs, baseline cases are run for ELV and OTV launch scenarios. For the baseline case, it is assumed that the satellite is launched in year 1 and a replacement launched in year 12, giving a 24 year mission life. The serviceable designs are launched in year 1 and serviced at the beginning of year 12. The refuelable design is serviced at the beginning of year 9.

5.1 Methodology

The the economic performance for the baseline, refuelable, and serviceable configurations are evaluated by comparing the Internal Rate of Return (IRR) and the Net Present Value (NPV). The IRR is a measure of return on investment based on cash flow. This type of comparison effectively decouples the analysis from external factors and allows comparison of a variety of investments with different capital expenditures and incomes. The NPV present value is a measure of the cash flow of a particular investment at a given IRR.

The IRR and NPV is calculated for the 12, 14, and 24 year program lifetimes based on the capital expenditures for the initial satellite and the replacement mission and the transponder revenues. Cash flows are spread over the lifetime of the program, and the standard formula used to compute NPV at the specified discount rate and the IRR. The following information is used to produce the cash flow table:

i. Annual capital expenditures

ii. Annual transponder revenues

iii. Tax rate

iv. Discount rate for NPV calculation

The cost inputs for the initial launch and replacement satellite are shown Tables V–29 and V–30, respectively. The transponder revenues are based on C-band and Ku-band transponder prices of $680,000 and $960,000 per year respectively (36 MHz transponders). The total revenue is estimated from transponder reliability data. The satellite revenue as a function of time is constant for the first four years and then begins to fall off as the number of failed transponders exceeds the number redundant transponders.

The revenue curves for the refuelable, closed configuration, and open configurations are shown in Figures V-26, V-27, and V-28 respectively. For each case, revenue is compared with that of the baseline satellite. For modeling purposes, a 38.6% tax rate and an annual operating cost equal to 10% of the transponder revenue are assumed. The NPV is based on a discount rate of 18%, which corresponds to the rate of return of the baseline ELV launch case.

5.2 Results

The model was run using the inputs described in Subsection 5.1 for the following cases:

i. Baseline satellite, ELV launch, 12 year life.

ii. Baseline satellite, OTV launch, 12 year life.

iii. Refuelable satellite, ELV launch, and a 12 year lifetime.

iv. Refuelable satellite, OTV launch, and a 12 year lifetime.

v. Refuelable satellite, ELV launch, and a 14 year lifetime.

vi. Refuelable satellite, OTV launch, and a 14 year lifetime.

Time (hr)	Mission Event
T_0	OMV moves OTV out of Space Station Control zone.
+2.2	First perigee burn by OTV.
+4.0	Second perigee burn by OTV.
+6.8	Third perigee burn by OTV.
+12.8	Fourth perigee burn by OTV.
+16.9	Apogee burn by OTV.
+41.3	Trim burn and rendezvous with 84° satellite by OTV.
+42.8	OMV separates from OTV.
+44.8	OMV rendezvous and docks with satellite.
+45.8	Module replacement and refueling operations for first satellite.
+54.1	System level checkout of first satellite.
+57.7	OMV demates from satellite.
+58.7	OMV docks with OTV.
+64.7	OTV performs east-west maneuver.
+112.7	OTV rendezvous with satellite at 144° W.
+114.7	OMV separates from OTV.
+115.7	OMV rendezvous and docks to satellite.
+116.7	Module replacement and refueling operations for second satellite.
+125.0	System level checkout of second satellite.
+132.8	OMV demates from satellite.
+133.8	OTV performs de-orbit & aerobraking maneuvers.
+140.1	OTV performs orbit raising maneuvers to 240 nm.
+142.1	OMV transfers OTV to Space Station docking area.
+143.1	MRMS grapples OTV and docks to Station.

Table V–28: Mission Timeline – Servicing Mission for Open Architecture Satellite

Capital Expenditure Item	Baseline ELV	Baseline OTV	Refuelable ELV	Refuelable OTV	Closed Design	Open Design
Satellite	64.2	64.2	68.5	68.5	64.8	69.4
Launch	40.0	34.2	40.0	34.1	34.5	34.7
OMV/OTV Charges	–	6.1	–	6.1	6.1	6.1
Space Station Support	–	1.6	–	1.6	3.0	4.0
Launch Support	1.6	1.6	1.6	1.6	1.6	1.8
Mission Operations	2.6	2.6	2.6	2.6	2.6	3.6
Insurance	26.0	13.5	27.0	14.1	13.7	14.4
Total	134.4	123.8	139.7	128.6	126.3	134.0

Table V–29: Capital Expenditures for Initial Satellite ($ M)

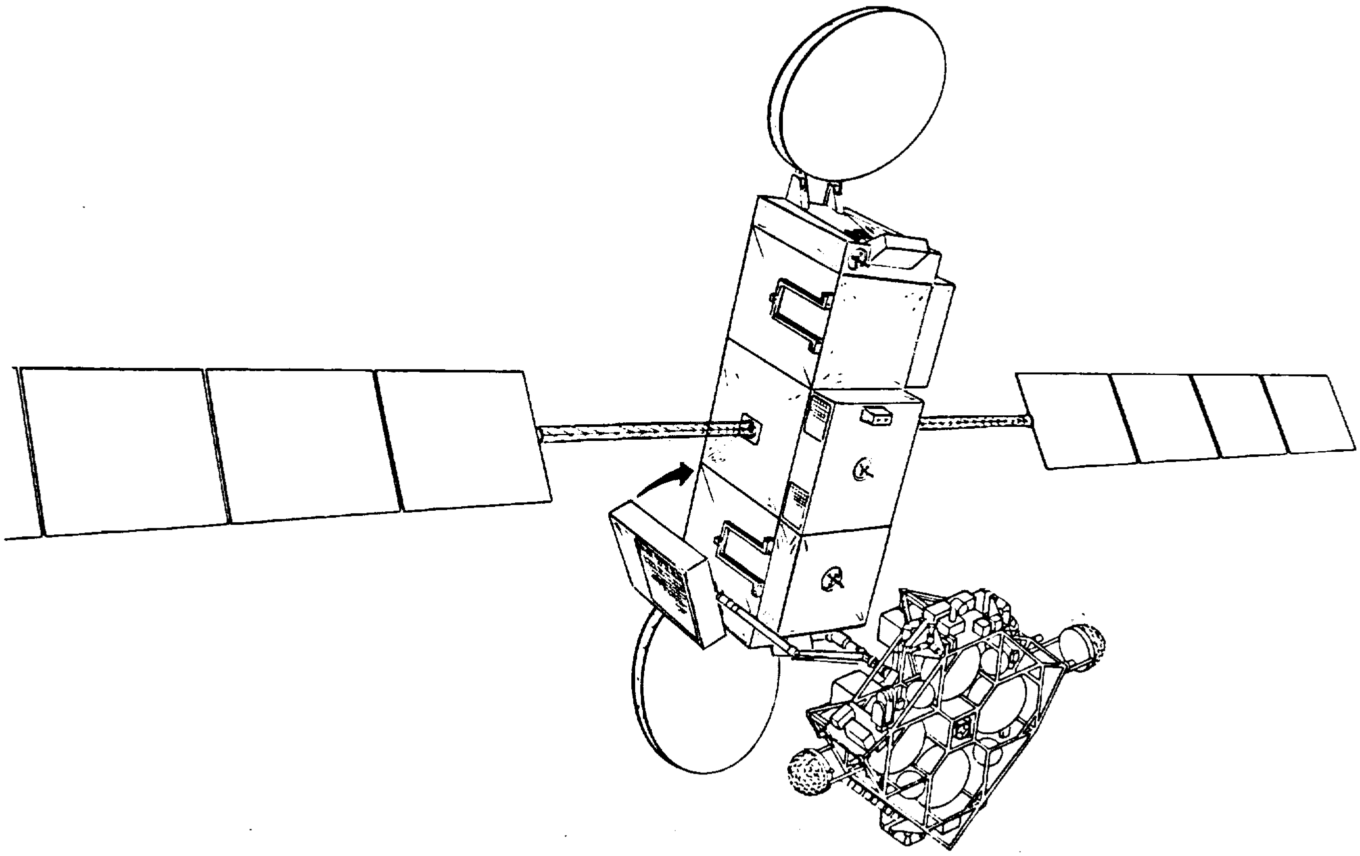


Figure V–24: Module Relocation/Replacement Operation

Capital Expenditure Item	Baseline ELV	Baseline OTV	Refuelable Design	Closed Architecture	Open Architecture
Replacement Cost	64.2	64.2	1.4	36.1	36.1
Launch Cost	40.0	34.2	5.8	24.6	23.4
OMV/OTV Costs	–	6.1	–	6.1	6.1
Space Station Support	–	1.6	1.0	3.3	3.3
Launch Support	1.6	1.6	–	3.2	3.2
Mission Operations	2.6	2.6	1.0	4.8	4.8
Insurance	26.0	13.5	3.5	12.1	12.0
Total	134.4	123.8	12.7	90.2	89.0

Table V–30: Capital Expenditures for Replacement or Servicing Mission ($ M)

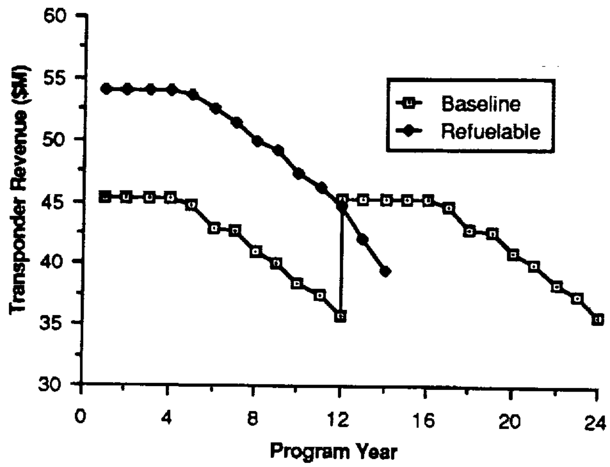


Figure V–25: Revenue – Refuelable Design

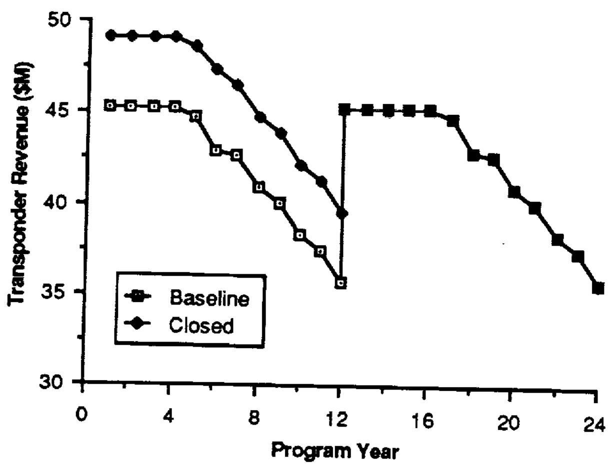


Figure V–26: Revenue – Closed Design

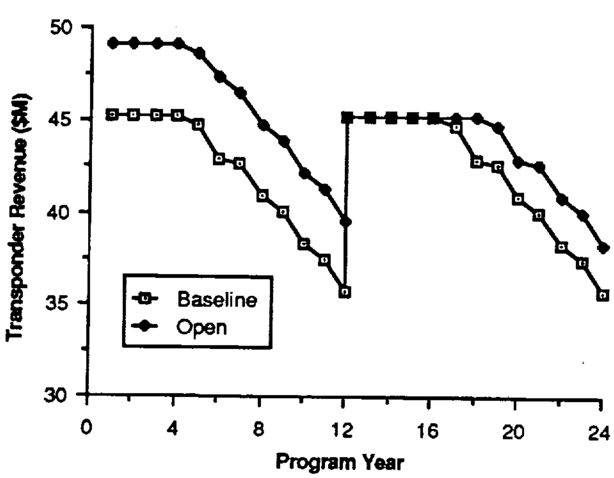


Figure V–27: Revenue – Open Design

vii. Baseline satellite, ELV launch, and a 24 year mission.

viii. Baseline satellite, OTV launch, and a 24 year mission.

ix. Open architecture serviceable satellite and a 24 year mission.

x. Closed architecture serviceable satellite and a 24 year mission.

The IRR and NPV for each of the above cases are shown in Tables V–31 and V–32, respectively. The results indicate that servicing improves the rate of return by 3.5% to 8.3% and the NPV value by $19.2 to $24.4 million. The performances of the serviceable scenarios relative to the baseline are summarized Tables V–33 and V–34.

Tables V–33 and V–34 indicate that the refuelable scenarios (Cases iii – vi) realize the largest improvement in economic performance, followed by the Closed (Case ix) and Open architecture (Case x) respectively. These results indicate that the economic performance is strongly correlated with the initial capital expenditures and the payload mass fraction. Of these two factors, the latter seems to dominate. The relation of these parameters to economic performance is shown in Table V–35.

In order to isolate the effect of the payload mass fraction on the economic performance two additional cases were run:

xi. Closed architecture configuration with 30 Ku-band (and 24 C-band) transponders for the entire mission.

xii. Open architecture configuration with 30 Ku-band (and 24 C-band) transponders for the entire mission.

The results of these cases are compared to cases ix and x in Table V–36.

Table V–36 clearly shows the influence of the payload size relative to the bus has on the economic performance. These results reiterate the importance of efficiently utilizing the available mass and power in order to achieve the maximum economic return. This is precisely the reason that the refuelable scenarios are the most efficient. The refuelable satellite converts fuel mass

Satellite Design	Mission Lifetime		
	12 Year	14 Year	24 Year
Baseline (ELV Launch)	18.0	–	14.5
Baseline (OTV Launch)	21.5	–	17.8
Refuelable (ELV Launch)	24.7	25.7	–
Refuelable (OTV Launch)	29.6	29.8	–
Open Architecture	–	–	21.3
Closed Architecture	–	–	23.8

Table V–31: Internal Rate of Return (%) for Various Configurations

Satellite Design	Mission Lifetime		
	12 Year	14 Year	24 Year
Baseline (ELV Launch)	-0.1	–	-11.8
Baseline (OTV Launch)	9.0	–	-4.7
Refuelable (ELV Launch)	19.1	23.8	–
Refuelable (OTV Launch)	29.3	33.4	–
Open Architecture	–	–	10.7
Closed Architecture	–	–	16.7

Table V–32: Net Present Value ($ M) for the Various Configurations (18% Discount Rate)

Satellite Design	Mission Lifetime		
	12 Year	14 Year	24 Year
Refuelable (ELV Launch)	6.7	7.7	–
Refuelable (OTV Launch)	8.1	8.3	–
Open Architecture	–	–	3.5
Closed Architecture	–	–	6.0

Table V–33: Increase in Rate of Return (%) Compared to Baseline Satellite

Satellite Design	Mission Lifetime		
	12 Year	14 Year	24 Year
Refuelable (ELV Launch)	19.2	23.9	–
Refuelable (OTV Launch)	20.3	24.4	–
Open Architecture	–	–	21.8
Closed Architecture	–	–	21.4

Table V–34: Increase in Net Present Value ($M) Compared to Baseline

Satellite Scenario	Initial Capital Expenditures ($M)	Payload Fraction (%)	IRR (%)
Baseline (OTV Launch)	123.8	30.0	21.5
Refuelable (OTV Launch)	128.6	32.8	29.6
Closed Architecture	126.3	27.9	23.8
Open Architecture	134.0	25.5	21.3

Table V–35: Effect of Capital Expenditures and Payload Mass Fraction on Economic Performance

Satellite Design	Number of Transponders			
	24 C + 34 Ku		24 C + 30 Ku	
	IRR (%)	NPV ($M)	IRR (%)	NPV ($M)
Open Architecture	21.3	10.7	17.8	-0.7
Closed Architecture	23.8	16.7	19.7	5.3

Table V–36: Impact of Number of Transponders on Economic Performance

which has no direct earning capability to payload mass which results in higher transponder revenues without an increase in the beginning of life (BOL) mass. The serviceable scenarios however suffer a significant increase in dry mass due to the scars required for servicing. The result is an increase in the satellite design, manufacturing and transportation costs without a corresponding increase in revenue.

Serviceable satellites have the potential for reduced insurance and transportation costs. While these are significant portions of the overall program cost, they do not tell the whole story. Care must be taken during the design stage to keep the cost of the satellite down and to maximize the payload fraction to ensure that the satellite is operating at maximum efficiency. Serviceable designs are similar to the current nonserviceable designs in that both must utilize the available mass and power to maximize their revenues.

6 Requirements on Station

This subsection suggests the services and operations that must be supported by the Space Station infrastructure in order to implement on-orbit assembly and servicing of commercial satellites.

6.1 Transportation Systems

In order to serve as a transportation node and orbiting service center, the Space Station requires three different transportation systems:

i. An earth to Space Station system.

ii. A recoverable orbital tug for short range operations with large payloads.

iii. A recoverable long range system for large payloads.

These systems are discussed in detail in the following paragraphs.

6.1.1 Earth to Space Station

Economical transportation to the Space Station is essential to commercial users. Development of intermediate to heavy lift launch vehicles for transportation directly to the Space Station would reduce the cost of the initial transportation leg.

Strong consideration should be given to development of automated docking systems for future Expendable Launch Vehicles (ELVs). This would reduce the burden on the Space Station crew by eliminating the role of the orbital maneuvering vehicle in ELV launches.

6.1.2 Orbital Maneuvering Vehicle

At least one Orbital Maneuvering Vehicle (OMV) is required to support remote servicing operations. The OMV is used for all phases of the servicing mission including:

- Transport of equipment from ELV or Shuttle aft cargo carrier in a parking orbit to the Station.
- Transport of payloads or equipment within the Space Station Control Zone.
- Transport and support of a remote servicing system.
- Retrieval of remote objects.

The dependence of the Space Station on the OMV warrants consideration of adding a second and possibly a third OMV to the inventory. This would allow an OMV to operate in a remote location for an extended period of time without adversely affecting Space Station operations. This suggests an alternate servicing scenario:

i. The OMV and remote servicer transported to GEO via the Orbital Transfer Vehicle (OTV).

ii. The OTV returns servicing debris to the Space Station while the OMV remains in GEO, either to perform additional operations or in a "hold" mode.

iii. Additional spares are transported to GEO by the OTV or an ELV.

iv. The OMV and servicing debris are returned to the Space Station via the OTV.

This scenario utilizes the contingency hold capability of the OMV in order to to remain in a remote orbit for up to nine months. This capability would reduce the servicing mission transportation costs by eliminating the need to transport the OMV on each servicing mission. This allows the cost of transporting the OMV to GEO to be spread among more users which in turn lowers the cost per user.

6.1.3 Orbital Transfer Vehicle

The proposed OTV configurations have the capability to transport large payloads from the Space Station to GEO at a much lower cost per kilogram than current systems. The retrievable nature of these designs increases the reliability of the system which may result in lower insurance rates due to the reduced risk. The ability to transport large payloads to GEO and return them to the Space Station is essential to the servicing scenarios presented in this report. In addition, the capability of the low thrust mode of operation is essential to the launch scenarios.

6.2 Space Station Facilities

In order to support commercial activities, the Space Station must provide storage facilities as well as the basic tools and services required to support assembly, maintenance, and servicing of commercial payloads. These facilities and services are discussed below.

6.2.1 Robotics

The Space Station crew requires support from robots operating both inside and outside the pressurized modules. These robots can relieve the crew from performing tasks ranging from the tedious and mundane to those that are potentially dangerous to humans. Potential tasks which may be automated include:

- Logistics operations.
- Satellite assembly and deployment.
- Remote inspection.
- Refueling.
- Handling of hazardous materials.
- OMV/OTV processing.

- Space Station maintenance.
- Remote servicing.

The range of activities at the Space Station and the workload suggest that more than one robotic system is required. The proposed Flight Telerobotic Servicer (FTS) and IVA robotic systems clearly have a place in the daily Space Station operations. Additional robotic systems are required for remote servicing and operation of the Space Station fuel depot.

The limitations of man-in-the-loop control suggest that the FTS may not be the best system for remote satellite servicing and that a simpler and lighter automated servicer such as the Integrated Orbital Servicing System (IOSS) should be developed. Handling of cryogenic and hypergolic fuels used in spacecraft propulsion systems is a potentially hazardous operation best performed by a robot. Since the fueling platforms will be located away from the Space Station, it is recommended that the fueling platforms have dedicated robotic systems.

6.2.2 Customer Servicing Center

The customer servicing center (CSC) should provide accommodations for storage, assembly, and servicing of commercial payloads. In order to support these activities the CSC should provide the following services:

- Internal storage and assembly area.
- Thermal control.
- Interfaces to Space Station communications, power and Data Management Systems (DMS).
- Video and lighting.
- Access for FTS, Mobile Remote Manipulator System (MRMS) and astronauts.
- Miscellaneous racks, fixtures and pallets.
- Standard EVA tools.
- Standard FTS tools and end effectors.

6.2.3 Fueling Depot

Provisions should be made for on-orbit storage of cryogenic and hypergolic fuels and nitrogen for the OMV, OTV and free flying spacecraft. These facilities should have the following provisions:

- Docking interfaces.
- Fluid transfer equipment.
- Fuel recovery/scavenging systems.
- Video and lighting.
- Robotics.
- Leak detection.
- Emergency fuel purge and contamination control systems.

6.2.4 Other Services and Equipment

Additional equipment required to support the proposed assembly and servicing scenario includes:

Berthing Facilities. OMV/OTV berthing facilities are required for storage and servicing of these systems. These facilities should have the capability for reprocessing and refurbishment.

MRMS is required for transportation of various payloads within the Space Station.

EVA Services by astronauts are required for routine and contingency operations in support of assembly and servicing activities.

Spacecraft Test Facilities are required for post assembly and prelaunch checkout.

RF Test Facilities are required to verify the performance of satellite antenna systems.

Docking and Berthing Facilities are required for the OMV, OTV, Shuttle and possibly ELVs.

7 NASA Course of Action

The task is to recommend a course of action to be undertaken by NASA that promotes the development and use of modular communications satellites. The discussion is divided into two parts:

1. NASA fee structure

2. Actions to promote modular satellites

7.1 NASA Fee Structure

Some thoughts and ideas are presented on a NASA fee structure for space operations involved in on-orbit assembly and servicing of communications satellites. The discussion is organized into four subsections:

1. What needs to be priced?

2. What is the purpose of the fee structure?

3. Discussion of the various issues associated with several pricing or fee structures.

4. Fee structure recommendations.

7.1.1 What Needs to be Priced?

There are a number of ways of looking at the question of what needs to be priced. The obvious answer is the service. But, what does that mean? Does it mean that NASA should have a set, fixed price for a service call? Or, does it mean that each component of the servicing is broken down (labor hours, IVA, EVA, RMS, time in the facility, parts, power, fluids, data, etc.) and charged for on some kind of hourly or quantity basis? Or, is there a combination of the two, that is a fixed charge for placing the satellite in the facility and taking it back out (no matter how much is required in, for example, RMS time and crew effort) and then a charge for "parts and labor" while the work is being performed? Clearly, these questions raise many operational as well as pricing issues. Some of these issues are discussed in detail in the sections which follow. The range of services to be provided to the communications satellite user can be broken down into three broad areas.

1. Non-facility services:

   - Launch to the Station
   - OTV from Station to GEO
   - Recovery at GEO
   - Return to Station

2. General usage

   - Positioning in the facility
   - Time simply present in the facility
   - Health maintenance in the facility (the minimum services needed to simply maintain the satellite in thermal control, data links, etc.)
   - Removal from the facility

3. Servicing

   - Assembly
   - Fueling or refueling
   - Repair
   - Retrofit/upgrading

Each of these services involves a large number of subactivities that can also be priced. The subactivities fit into five general categories:

- Labor (crew time for IVA or EVA, planning, scheduling and preparing for the activity, operating the RMS, etc.)

- Consumables (power, fuel, etc.)

- Telemetry or data transmission

- Parts

- Equipment usage (RMS, EVA suit, OTV, etc.)

Each of these sub-activities can be priced either in terms of time, volume consumed, or by discrete item. This would allow the facility manager to set up a price list for all services. For example, crew time could be charged for at the rate of say \$20,000 per hour, use of the EVA suit at say \$100,000 per hour, power at say \$2,500 per kilowatt hour, fuel at say \$4,000 per liter, and a new battery at \$10,000 (includes cost of transportation). Therefore, if a satellite were to be refueled and have a new battery installed, one could estimate the amount of each of these and other activities would be required and develop a price. This is all very straight forward – the hard part is in determining how much should be charged. This area is discussed in greater detail in the next subsection. Before we leave this issue, however, it should be noted that each of the three broad areas has certain characteristics that may influence our options when determining pricing structure.

7.1.1.1 Non-Facility Services. These services involve flight issues and, it can be argued, the existing way of buying launch services may have already established precedents for the fee structure. It may also have provided some idea as to price range. As was established in the earlier study, the communications satellite industry has to see a tangible benefit before they will change their way of operating and use the Space Station. As a result, the fixed price method with some added charges for optional services appears to be the most likely structure for this area.

7.1.1.2 General Usage. General usage appears to be a rather predictable area. Once some operational experience is gained, it should be rather easy to know what is required to position satellites in the facility, hook up health maintenance capabilities, and remove it from the facility. These charges again would lend themselves to a fixed price scheme. The issue of time actually in the facility, like the room charge at a hospital, can be determined and charged at a fixed hourly or daily rate. The key to this entire area is predictability. There should be no unknowns so the scheme for pricing should be very predictable. Of course, some customers may desire some special services as part of the general usage category and these could be accomplished for either flat fees or increased hourly rates depending on the service desired.

7.1.1.3 Servicing. Servicing is the least predictable area. While estimates can be made, the exact number of man hours needed or other items consumed is difficult to calculate with precision in advance. This area, like a standard automobile repair facility, lends itself to a price list type of structure. In this structure rates are established for labor and consumables and parts are charged based on a published catalog or price list.

The problem faced by this method for the Space Station is that there is no precedent for this type of work and it is difficult to determine what the initial customer should be charged. This is a problem in that once labor rates and catalog prices are published, these are rather difficult to change in an upward direction except in small increments. As a result, significant care should be taken in the initial price setting task.

The natural solution to this problem is to be conservative and set the prices high so that they can be adjusted downward later if experience shows the work can be done less expensively. Unfortunately, this strategy may also succeed in pricing the services so high that customers choose not to use the facility.

7.1.2 Purpose of the Fee Structure

The results of the pricing work performed by both the Coopers & Lybrand and JPL/Cal Tech groups (for NASA Headquarters, Space Station Utilization Directorate,) suggests the following points:

- Pricing policy should encourage early use.
- Policy should be flexible and adaptable.
  - Predictability is important (rules of the game).
  - Predictability does not require unchanging prices.
- All subsidies should be explicit.
- All users should be subject to prices.
- Mechanisms must exist to allow customer self-selection of priorities.

The one issue that is not part of that list is cost recovery. It was felt that the Space Station should be viewed as a national asset and, as such, the importance of recovering costs was secondary to the overall benefits that could be derived. Also, it was felt that the Space Shuttle was over sold on its ability to pay for itself and that that error should not be made again. Therefore, whatever revenue was derived from charging for the services was a benefit but cost recovery should not be considered the goal of the pricing policy.

Clearly, such a philosophy substantially changes the purpose of a fee structure or pricing policy. If it is not required that costs be recovered, at least in the short run, then the purposes of the pricing policy becomes to influence customer behavior and allocate resources. That is, we make expensive those things that are scarce (i.e. crew time) and relatively inexpensive those things that are more plentiful (i.e. outside storage space). In this way we try to influence customer activity.

For example, if EVA activity is made more expensive than robotic manipulation, you encourage the customer to design his spacecraft in such a way that he facilitates and promotes robotics while discouraging EVA. If one wishes to strongly emphasize this point one could even provide a subsidy or discount for satellites that promote the use of robotics. An example would be that all satellites manufactured with the capability of robotic changing of major components would receive a 15% discount on all services conducted aboard the Space Station.

Pricing policy can also be used to determine the priority of a payload for servicing. A number of mechanisms can be used. If supply exceeds demand, then there is little problem. However, if demand exceeds supply (either overall or at key points in time) then either an auction mechanism or the ability to purchase a higher priority slot serve as mechanisms for self selection. For example, if a number of satellites are scheduled for routine maintenance and have paid for their time in the schedule and another satellite has a failure, then a mechanism might exist where by that satellite owner could purchase a priority or emergency place in line and bump others out. The system might work something like the current pricing of transponders where we have preemptable and non-preemptable classes.

Whatever the pricing policy selected, careful consideration must be given to the long term impacts of the system and its ability to accomplish two seemingly contradictory objectives. These are, first, to provide consistent predictable rules of the game so that customers can determine in advance their costs and make selections as to the levels of priority they wish and, second, to allow prices to change and raise over time to become a mechanism to effectively allocate resource and eventually begin to recover operational costs. The report prepared by Coopers & Lybrand suggests a method for accomplishing this.

One final issue with respect to the pricing policy needs to be addressed. The effort to price services low to encourage early usage works well for such areas as laboratory usage for microgravity materials science which is recognized as an emerging area of space activity. The communications satellite area, however, is considered a mature, profitable business area able to pay its own way. As such there may be considerable resistance to low prices and not recovering large portions of operating cost. As was discussed in our earlier work on this subject, the price for the full up package (launch to Station, work at Station, transport to GEO or other orbit) must either be lower cost or clearly more beneficial to the satellite owner or they will bypass the Station and go directly to GEO as they do now.

In short, it is our belief, that the fee structure should promote usage as a primary goal. As a result, fees, on whatever basis they are charged, should be kept low. In addition, mechanisms should be developed, such as those suggested in the Coopers & Lybrand report, that allow prices to raise over time as demand increases.

However, there are serious consequences to this policy especially with respect to the communications satellite area. With the government providing what are, in effect, massive subsidies to get the activity started and thereby encourage builders to shift their methods of production to accommodate use of the Space Station, there will be several parties hurt and, once the transition is complete, satellite users will, in effect, be captured by the Space Station policy.

7.1.3 Fee Structure Issues

The preceding sections have discussed what needs to be priced and what purposes of the pricing or fee structure might serve. We now turn to some pragmatic issues which build on those points. The first comment is that whatever system is selected it must be consistently applied over a significant period of time to allow the customer to plan. It is also desirable that the system be relatively easy to understand.

Unfortunately, simplicity is a double edged sword. Simple systems are easy for the customer to understand but, in general, they lack the sophistication to adopt to the changing economic realities over time as more is learned about how this activity is actually conducted. As a result, systems which appeared simple at the outset require total revision at some point and this radical change in the rules of the game, if it is possible at all, upsets customers greatly (if it is not possible then the provider continues to suffer economic harm from continued operations).

There are many systems that could be adopted as a fee structure for servicing communications satellites on the Space Station. Let us assume that for all approaches the transportation to Space Station is carried out using either Shuttle or ELV and is priced separately. We start at the point where the satellite is sitting outside the Station waiting for the service provider to take charge of it. Three pricing options are discussed:

1. Fixed Price Fees
2. Sliding Scales for Prices
3. Combination of Fixed and Sliding Scale

7.1.3.1 Fixed Price Fees. The first option is a fixed price option similar to that used for satellites on the Shuttle. That is a single (or perhaps several based on size or type) fixed price for a complete service in using the Space Station facility. It could also be done just like the Shuttle and a price determined for the entire capacity of the service facility and customers charged for the percentage of that space they occupy.

The advantage of this approach is simplicity. All activities are bundled and the customer knows what must be paid. Of course, in order to provide predictability, prices must be fixed for some period of time such as four to five years or more (they can vary with outside parameters such as inflation but not with respect to base charges). While this type of system possesses some advantage to the customer, assuming the initial price selected is not considered prohibitively high, there are serious disadvantages for the operator.

Since there is no operational experience on which to base the initial pricing and that price must be fixed for a number of years, the operator looses all flexibility in the system. Whatever price is charged initially, right or wrong, they are stuck with that price and the probability of the price being wrong is very high. Therefore the selection of this pricing policy implies a decision on the operator's part to accept a subsidization role (perhaps in an introductory offer initially and less so later) for a significant period of time. This means that no matter what happens to costs, the price stays the same.

The other disadvantage is that it eliminates the ability of the operator to influence the customers behavior. With a fixed price the customer is not aware or concerned about the cost of relative options for the use of different methods of servicing (EVA versus robotics). The customer is paying a fixed price for the services and is neutral as to how the job gets done. Again the operator can either do well or do poorly (in an economic sense) based on how efficiently they can perform the work. However, the tendency is to force fixed prices down over time and the opportunities for the operator to do well economically are not as great as they are to do poorly.

7.1.3.2 Sliding Scale Fees. The second pricing method is in a sense the opposite of fixed costs. That is the development of prices for each particular activity or sliding scales for prices so that the customer is charged for each discrete activity and/or material that are used. The advantages of this system to the operator are that they are assured that there is little difference between the costs of providing the service and what they are able to charge, they can influence the behavior of the customer by making certain alternatives more or less expensive, and they have greater flexibility in changing prices. This last issue is because with so many items are priced, changes in a few are relatively minor events to the customer and may go unnoticed and can usually be justified in terms of increased costs to the operator.

Of course, the disadvantage to the customer is the greatly increased complexity of the system and the resultant loss of predictability for planning purposes. Some of this predictability is reattained, however, if price lists are public and operational experience has given the customer and/or the operator the ability to predict with some accuracy what a particular activity is likely to cost. A major problem, however, is faced by the initial customers who have no operational experience on which to base their forecasts of cost.

7.1.3.3 Combined Fixed and Sliding Scale Fees. The obvious other alternative is some combination of these two methods. As was suggested in an earlier section, some activities lend themselves to fixed prices because of their relatively routine and predictable nature while others lend themselves to price lists. This approach has a number of obvious advantages. However, in dealing with some issues a few suggestions may be in order. A lower introductory fixed price for the fixed price services might be given to encourage early usage. For the price list services, consideration might be given to paying by the price lists with a total, not to exceed, price determined in advance until some operational data is developed. While this does not eliminate all risks to the customer, it puts a cap on the risk. Of course, both of these suggestions imply the government's willingness to take the losses for both the introductory stimulation and incorrect estimates of price list costs. However, without such a willingness it is difficult to motivate initial users.

7.1.4 Fee Structure Recommendations

The question of fee structure and pricing must be dealt with in the context of the larger Space Station pricing policy question which is being studies at NASA Headquarters.

We do not suggest actual dollar amounts because it is far too early for that level of specificity, but have give recommended methodology. The combined fixed and sliding scale fees as discussed in paragraph V-7.1.3.3 is recommended.

We believe that for the customer, knowing the actual dollar price is far less important than knowing what the "rules of the game" are so that they can calculate what their fees will be once actual amounts are known.

7.2 Promotion of Modular Satellites

This subsection provides some thoughts and issues concerning what actions NASA might take to promote the use of modular satellites and assembly, test and refurbishment at the Space Station.

7.2.1 Current Situation

The domestic commercial communications satellite manufacturers (Ford Aerospace, Hughes and GE-RCA Astro) have invested substantial capital in plant, equipment, manufacturing to manufacture satellites using current technology. They each also operate relatively profitable businesses in the production of both commercial and government satellites. As was made quite clear in the research performed for the initial phase of our work for NASA Lewis Research Center, they are not currently motivated to change from this successful pattern.

When the initial financial models were built for the servicing and repair of communications satellites, it became a basic assumption of the exercise that, unless NASA could demonstrate that stopping at the Station was either financially beneficial or significantly enhanced the capability of the system, the manufacturer/owner/operator would by-pass the Station and do business as usual. This basic assumption remains quite valid in this portion of the study.

In fact, in order for the manufacturer to be motivated to change behavior, it must be demonstrated that stopping at the Station is so beneficial it will show a return on investment adequate to offset the entire cost of required R&D for and the actual changes in production techniques needed to use the Station within a relatively short period of time (e.g. 3-5 years). As currently planned, no one has indicated that the costs of stopping at the Station will be sufficiently beneficial to provide adequate offset.

Although the insurance community does feel insurance rate benefits will be derived from assembly and repair at the Space Station, it will come only after the system has been adequately demonstrated. The insurance industry personnel interviewed also indicated that they did not feel the insurance industry would lead any movement toward use of the Space Station. It is highly unlikely they would require such use as a condition for coverage (though eventually preferential rates may be given). Here again, even reduced insurance rates will not provide adequate financial rewards to offset the development and other costs associated with the change.

7.2.2 Available Options

Given this situation, the options available to NASA to stimulate use of a servicing facility are limited:

1. Waiting in hopes that demand for such a facility will eventually develop;

2. Building the facility (including an OTV) and providing owner/operators use of the facility at little or no cost in hopes that it will, in fact, be used;

3. Requiring a modular design (like Solar Max or a more advanced version) and assembly and test at the Station for selected NASA scientific satellites;

4. Initiating a major government wide (NASA, NOAA, DOD) effort to require most if not all government procured satellites to be modular and use the Space Station for assembly, testing and repair.

7.2.3 Pros and Cons of the Options

The first option, as was made clear in the discussion of the current situation above, is very unlikely to succeed. All of the economic incentives are wrong for demand for such a facility to develop on its own.

The second option is also not very desirable. It requires a major up front investment by NASA that may not provide adequate incentive for manufacturers to change their methods of production and operations even if the services are provided for free. The cost of change from the manufacturer's point of view is quite high and must be successfully amortized over a number of sales to be offset and show an economic benefit. While a zero cost for use of the Station facility and OTV may provide adequate return if sufficient sales can be made, unless all manufacturers change, the one changing may perceive a competitive disadvantage during the change. Also, a real risk exists that NASA policy might change and begin charging for the facility/OTV may provide adequate return if sufficient sales can be made, unless all manufacturers change, the one changing may perceive a competitive disadvantage during the change. Also, a real risk exists that NASA policy might change and begin charging for the facility/OTV usage creating a major economic disincentive. Even if this did not happen during the transition period, it almost certainly would happen eventually putting at least a cap on the economic potential of the decision. In short, while the second option may stir some action, it is unlikely to be a sufficient motivator to cause change.

The third option provides several advantages and incentives to the manufacturer. First, NASA funding would in whole or in part offset the costs of development, design and retooling to build a modular, repairable satellite. Second, it would allow the manufacturer to develop an expertise in such technology that may be transferable to commercial customers in particular if it was felt that this was the start of a trend. Finally, the construction, launch, assembly, testing and use of a satellite built in such a manner would provide proof of the concept. Such an event would have an impact on the insurance market. In addition, it would have a positive engineering impact if the new satellite were perceived to be more technically advanced and more capable than one assembled and tested on earth and launched directly. The satellite need not be geosynchronous to accomplish most of these goals.

The other issues are of importance in looking at this and the following option. These are, first, the importance of the pricing policy as discussed in Subsection V-7.1.2. Even if several successful NASA satellites are assembled on orbit, that will not necessarily be adequate incentive to cause manufacturers to change if the economic incentives are not there. Second, demonstration projects are double edged swords. That is, if they go well they can make a program. If they go poorly, that is have significant cost over runs, technical or performance problems, they can kill a program forever.

The fourth option is simply a far larger application of option three. It has two additional benefits. First, it virtually certainly will cause several if not all manufacturers to become involved in the transition program. And, second, it will insure the manufacturers that there is a sufficiently large market available or products made in this manner to encourage them to do all production including commercial, in this way. It should be noted, however, that this action would cause a large number of satellites to move through the Station which may cause it to become a bottle neck in the production sequence causing both management problems and, from the DOD's point of view, security problems.

7.2.4 Recommendations

It is recommended that either

i. a modular design be required with assembly and test at the Space Station for a selected NASA satellite; or

ii. a government wide effort be initiated to require most government satellites be modular and use the Space Station for assembly, testing, and repair;

if NASA hopes to stimulate satellite manufacturers to use the Space Station for assembly, testing, and repair.

It is suggested that NASA identify suitable NASA satellites for potential modular design, fund some preliminary feasibility and design studies to do proof of concept work on this issue, and conduct whatever activities are required to foster this concept within the other government agencies who utilize satellites.

There is one additional and fundamental question that must be asked: should NASA and the government be doing this at all? In a sense, NASA's activity is driving demand based on NASA's desire to build such a facility. There are a number of economic arguments and historical examples such as the supersonic transport that would argue against such an activity. Though this report does not address this issue, it should be part of any future study of this issue.

8 Conclusions

The overall purpose of this task is to study the feasibility of on-orbit assembly and servicing of commercial satellites. Conclusions are presented in seven categories:

1. Space Station infrastructure
2. Serviceable satellite designs
3. On orbit assembly scenarios
4. On orbit servicing scenarios
5. Analysis of economic performance
6. Impact on the Space Station
7. Recommended NASA course of action

The results of this study indicate that servicing offers improved economic performance provided that the satellite development and transportation costs are not greatly affected. However, servicing has the effect of reducing the payload fraction (the mass of the payload versus the dry mass of the satellite) which in turn diminishes revenue generating capacity. It is recommended that the serviceable designs be given further study with respect to these factors.

8.1 Space Station Infrastructure

The analysis of the planned NASA infrastructure included a survey of the proposed transportation systems, Space Station facilities, and remote servicing systems. The purpose of this analysis is to assess the feasibility of on-orbit assembly and servicing and to determine any design drivers for future satellites. The following conclusions are reached:

- The planned Space Station infrastructure will support on-orbit assembly and servicing.
- The Integrated Orbital Servicing System should be considered for the first generation remote servicing system.
- The Orbital Spacecraft Consumables Resupply System is too large for commercial satellite servicing applications. A smaller refueling kit or OMV scavenging system should be developed.

8.2 Serviceable Spacecraft

A subsystem level analysis of the baseline design was conducted and three serviceable configurations were developed:

i. A refuelable design may be refueled on orbit using the OMV, OTV and the remote servicer. The decreased fuel mass allows the satellite to accommodate a greater number of transponders.

ii. A closed architecture design allows replacement of many of the bus and payload subsystem components as well as refueling.

iii. An open architecture design allows replacement of many of the bus and payload subsystem components as well as refueling. The open design allows for on-orbit storage of the used orbital replacement units.

The following conclusions about serviceable satellites are reached:

- The major factor that limits the lifetimes of most GEO satellites is radiation degradation. Improvements in radiation hardening techniques for electrical components, composites, and solar cells should be researched.
- Solar array degradation becomes a major design driver. Improvements in solar cell technology will be required. Gallium arsenide and indium phosphide cells which are more resistant to radiation should be developed.
- Spacecraft can be easily scarred for remote assembly and servicing.
- Serviceability imposes a 16% to 32% increase in the satellite dry mass.
- Modularity reduces the integration and test costs by approximately 10%.

8.3 On Orbit Assembly

Scenarios were developed for the Open and Closed architecture designs ranging from deployment of appendages to subsystem level assembly. Following assembly and test operations, the Space Based Orbital Transfer Vehicle (SB-OTV) is used to transport the satellite to GEO. The following conclusions regarding on-orbit assembly are reached:

- On orbit assembly can be accomplished with the planned NASA infrastructure.
- Assembly at the Space Station reduces the risk of launch failures and consequently should result in lower insurance costs.
- The SB-OTV reduces the launch costs by 16%.
- "Space available" launch scenarios should be evaluated as a means of reducing transportation costs. These scenarios encourage complete utilization of launch vehicle capacity and allow launch costs to be spread among several users.

8.4 On Orbit Servicing

Servicing scenarios are developed for the refuelable, open architecture and closed architecture designs. The servicing scenarios ranged from on-orbit refueling to subsystem level replacement.

In summary, the following conclusions regarding on-orbit servicing are reached:

- Satellite servicing can be performed in-situ with a simple robotic servicer.

- Not all subsystems can be serviced with current technology. The level of servicing is, however, sufficient to restore the satellite to original condition.

- On orbit servicing can be performed for 30% less than complete replacement.

- Space debris is an issue that requires further study.

8.5 Economic Performance

The economic performance of the serviceable designs is evaluated and compared to the baseline with the following results:

- The serviceable designs give greater rate of return and net present value (NPV) than the baseline design.

- The refuelable design offered the best performance followed by the closed and open architectures respectively. Tables V-37 and V-38 summarize the improvement in economic performance of the serviceable satellite designs relative to the baseline satellites.

- The economic benefit of servicing is strongly correlated with initial capital expenditures and payload mass fraction. Serviceable designs must continue to efficiently use available mass and power.

The question can be asked why the serviceable designs of this section show better economic performance than the baseline design, but the retrieval operations of Section III do not. Servicing has the advantages of lower transportation costs via multiple missions which can be scheduled. Repair scenarios suffer economically from the high reliability of placement, the high percentage of non-repairable failures, and high relaunch costs.

Satellite Design	Mission Life (yr)		
	12	14	24
Refuelable (ELV launch)	6.7	7.7	–
Refuelable (OTV launch)	8.6	9.8	–
Open Architecture	–	–	3.5
Closed Architecture	–	–	6.0

Table V-37: Increase in Rate of Return (%)

Satellite Design	Mission Life (yr)		
	12	14	24
Refuelable (ELV launch)	19.2	23.9	–
Refuelable (OTV launch)	20.3	24.4	–
Open Architecture	–	–	21.8
Closed Architecture	–	–	21.4

Table V-38: Increase in NPVs ($M)

8.6 Space Station Impacts

On orbit assembly and servicing can be supported by the Phase II Space Station. In order to reduce the impact of these activities on the Space Station, the following changes are recommended:

- At least one OMV should be added to the fleet to allow for extended remote operations.

- The fueling platforms should have their own dedicated robotic systems for automated fueling.

- Space Station insurance issues require further study. More information is needed to determine the effect of the Space Station on insurance rates.

8.7 NASA Course of Action

It is recommended that NASA take the following actions to encourage commercial satellite users and manufacturers to build serviceable satellites:

- Pricing policies should be developed to encourage commercial users to utilize the Space Station facilities in the most efficient manner.

- Preliminary prices should be published that allow commercial users to estimate the cost of on-orbit assembly and servicing.

Section VI

OTV – SATELLITE INTERFACES

The purpose of this task is to provide the communications satellite requirements needed by the General Dynamic Corporation Study, *Centaur Operations at the Space Station,* (NASA/LeRC NAS3-24900). The requirements include the following:

- Physical interfaces with the Centaur-G Prime
- Mission requirements
- Payload characteristics
- Facility requirements
- System tests

This section is divided into two parts:

1. An outline of the technology demonstration mission at the Space Station being studied by General Dynamics Corporation, and
2. A summary of the OTV – satellite interface requirements for the Centaur.

This information was conveyed to General Dynamics personnel via meetings, telephone conversation, and mailed material.

1 Centaur Operations at the Station

Figures VI-1 through VI-6 summarize the material showing the Centaur operations at the Space Station technology demonstration material. This material was supplied to Ford Aerospace by General Dynamics, Space Systems Division.

A key issue is the payload adaptor concept between the Centaur, which is envisioned as acting as an OTV (orbital transfer vehicle) between LEO and GEO, and the satellite(s) comprising the payload. The capacity of the Centaur is such that several "garden variety" communications satellites or a single large platform can be placed in GEO orbit simultaneously.

2 Satellite Interface Parameters

Table VI-1 summarizes the satellite parameters needed for specifying the OTV – satellite interface. Parameters are presented for four different satellite types:

1. RCA Americom K2 (3-axis)
2. Hughes HS-393 (spinner)
3. Ford small platform
4. Ford large platform

Figures VI-7 through VI-10 show layouts of the satellites. Figure VI-11 shows the layout of the large geostationary orbit communications platform.

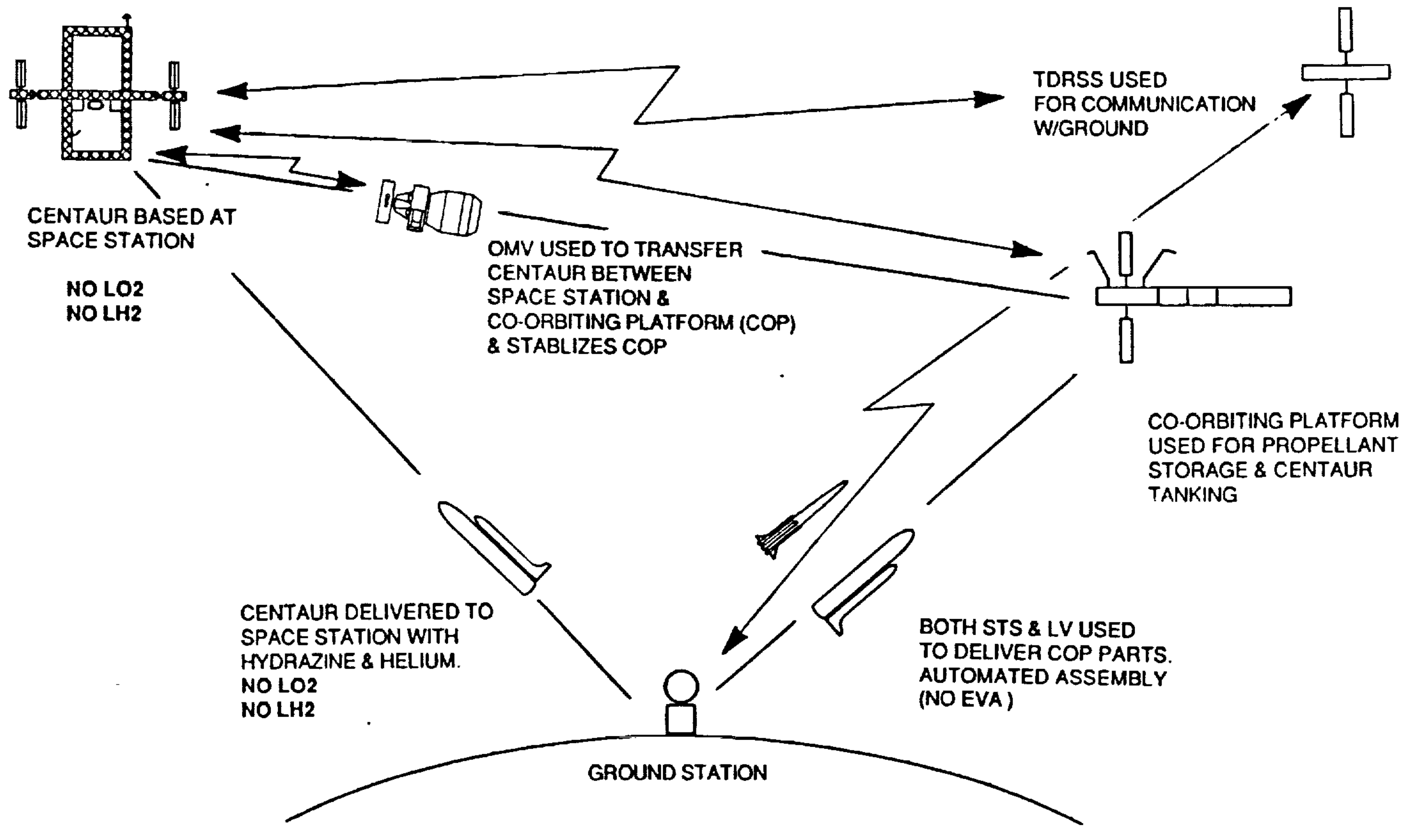


Figure VI–1: Architecture for Centaur Operations at the Space Station

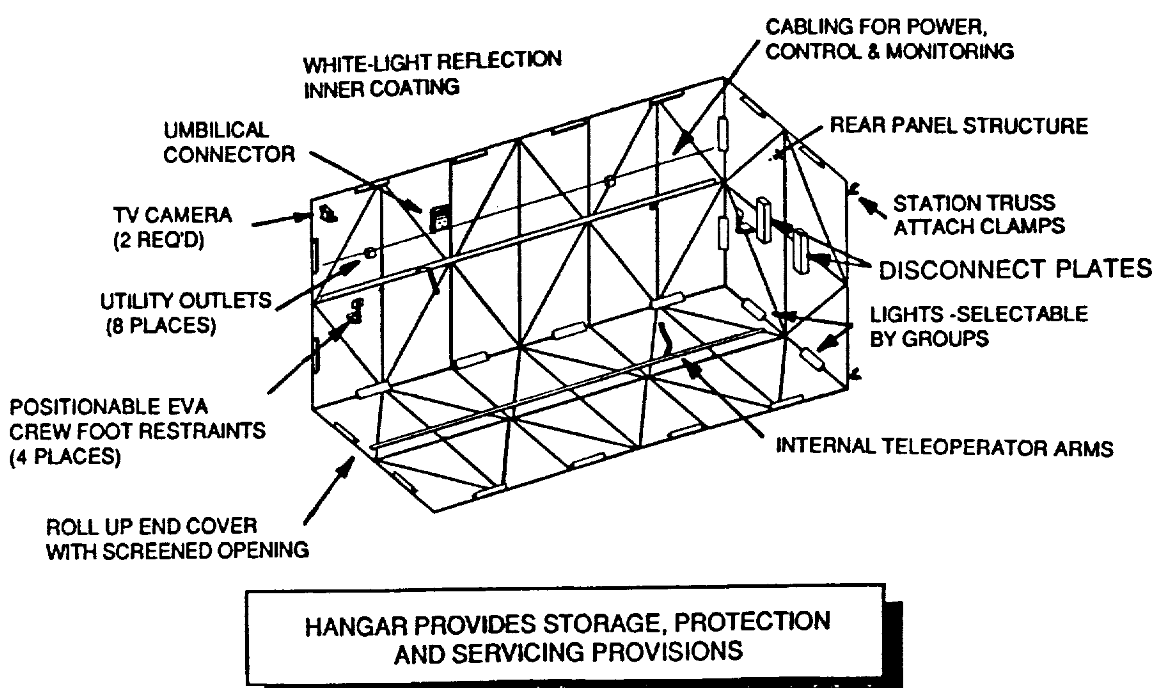


Figure VI–2: Hanger Facilities for Centaur Operations at the Space Station

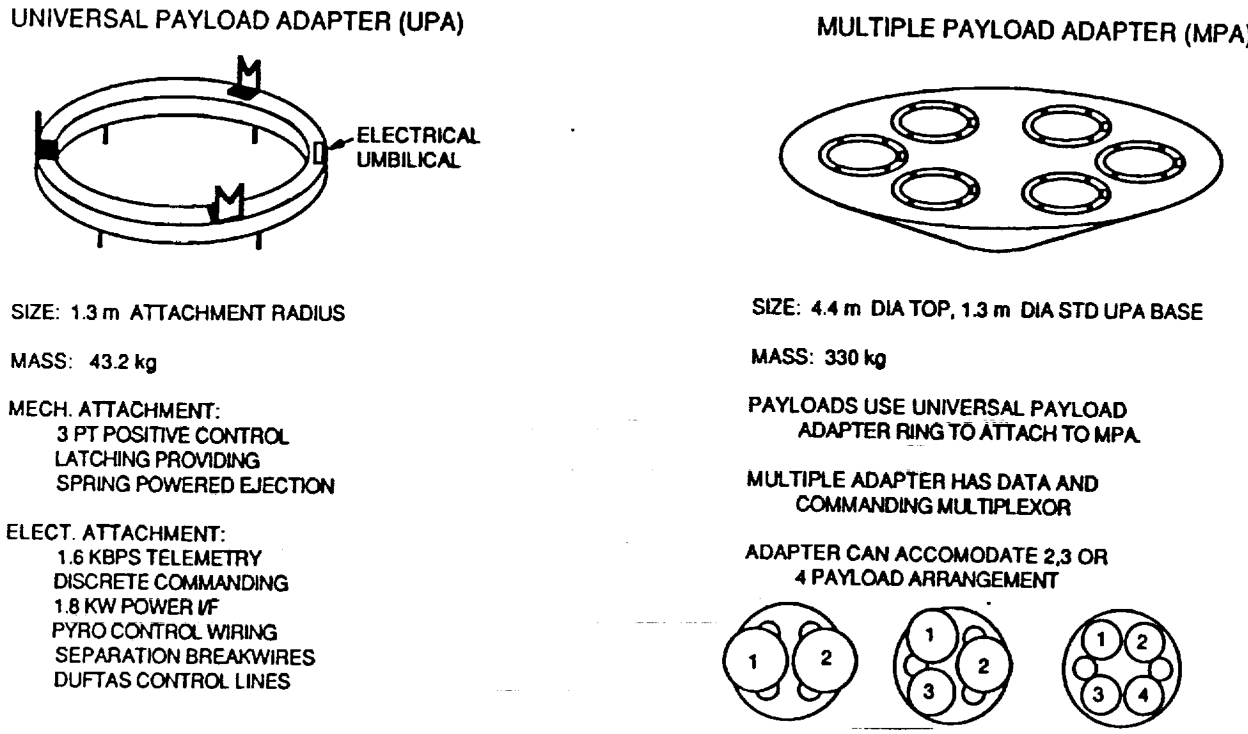


Figure VI-3: Payload Adaptor Concepts for Centaur Operations at the Space Station

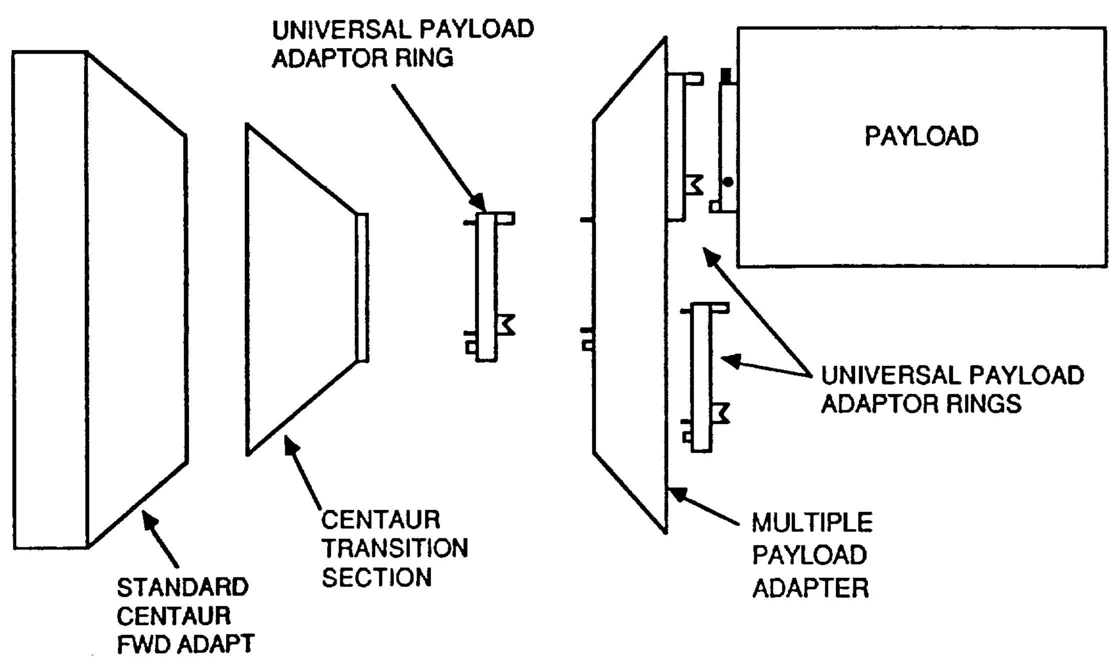


Figure VI-4: Centaur Payload Integration

SATELLITE NAME	WEIGHT (kg)	LENGTH (meters)	DIAMETER (meters)
WESTAR 12	660	2.4	2.3
GOES - L	1060	2.4	2.3
GALAXY KA-2	1320	4.5	2.3
GSTAR	1340	4.5	2.3
INTELSAT VII	1360	6.8	2.1
SBS/IBM	1360	6.1	2.1
GLOBAL POSITIONING SYSTEM (4 FLTS)	1410	3.0	2.3
FLTSATCOM	2040	4.2	3.0
HF DIRECT BRDCST PLTFRM	6360	9.1	4.6

SAMPLE MISSION MANIFESTING OPTIONS

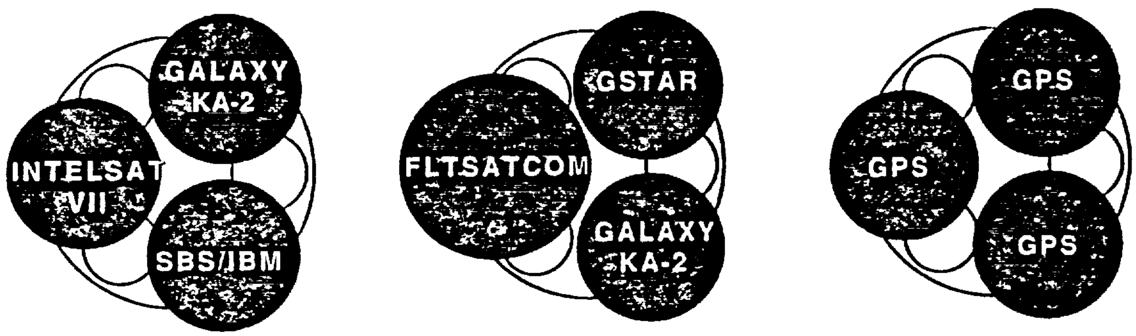


Figure VI–5: Centaur Mission Model for 1997 Flight

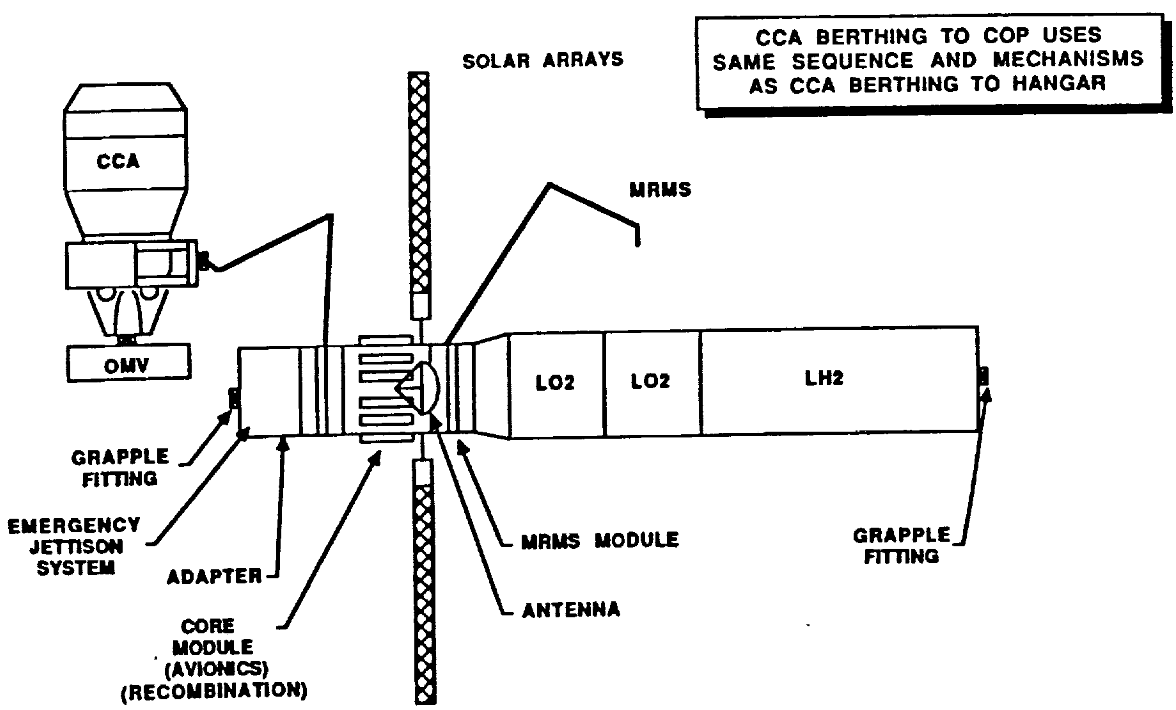


Figure VI–6: Accomodations Required at Space Station for Technology Demonstration Mission

	3 - AXIS RCA American K2 (FOLDED)	HAC HS-393 SPINNER	FACC SMALL PLATFORM (FOLDED)	FACC GPBS LARGE PLATFORM (DEPLOYED)
• MASS (KG)				
- EOL	990	1133	1411	6600
- BOL	1200	1377	2068	8060
• MOMENTS OF INERTIA, ($KG\text{-}M^2$)				
- ROLL (X)	1570	1713	1985	48,025
- PITCH (Y)	1350	1060	1685	1,131,120
- YAW (Z)	1290	1713	1637	1,179,145
• POWER				
- ON-ORBIT, EOL S.S	3000	2900	4400	11,000
- TRANSFER ORBIT	300	300	350	600
- STORAGE	100	100	100	250
- VOLTAGE	28-32 VDC	28-32 VDC	28-32 VDC	28-32 VDC
• TT&C				
- FREQUENCY	Ku-Band	Ku-Band	Ku-Band	S-Band
- DATA RATE	1000 Bps	1000 Bps	1000 Bps	1000 Bps
• THERMAL CONTROL				
- ROTATION RATE (Rpm)	0.1	0.1	0.1	0.1
• ACCELERATION LIMITS				
- AXIAL (g MAX.)	4.5	4.5	4.5	0.1
- LATERAL (g MIN.)	0.2	0.2	0.2	0.1
• STRUCTURAL FREQUENCIES				
- AXIAL (Hz)	35	35	35	0.1
- LATERAL (Hz)	15	15	15	0.1

Table VI–1: Satellite Parameters for OTV – Satellite Interface

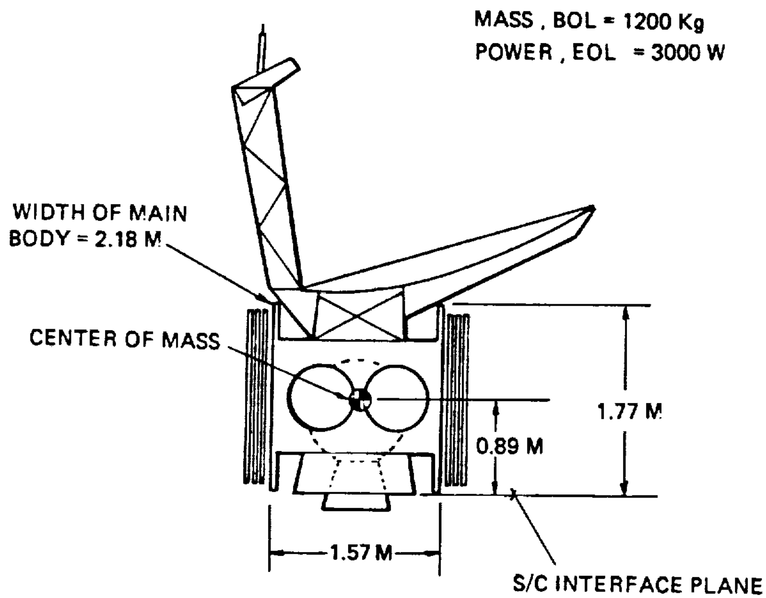


Figure VI–7: RCA Americom K2 Satellite with Solar Array Folded

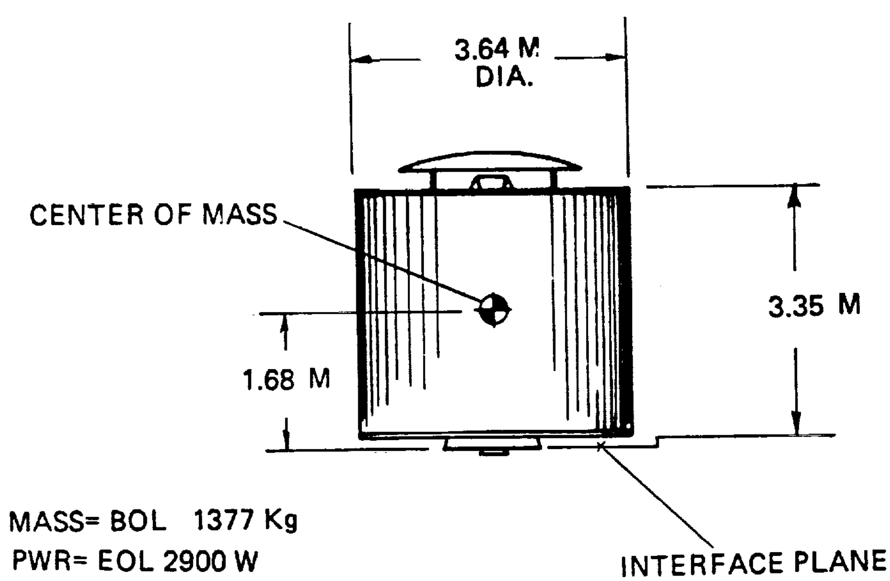


Figure VI–8: Hughes HS-393 Satellite

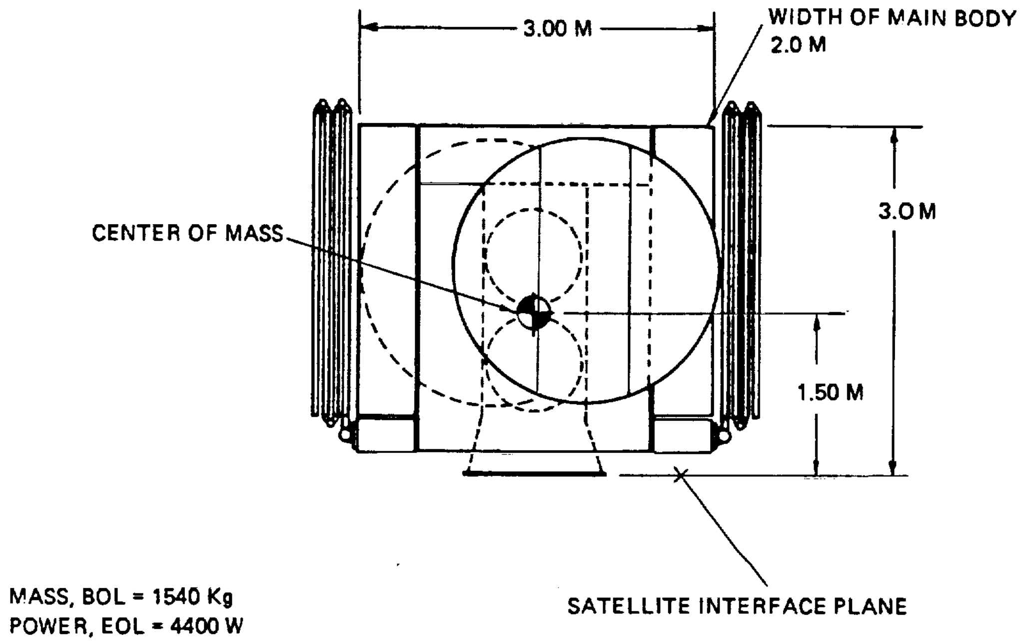


Figure VI–9: Ford FS-1300 Satellite with Solar Array Folded

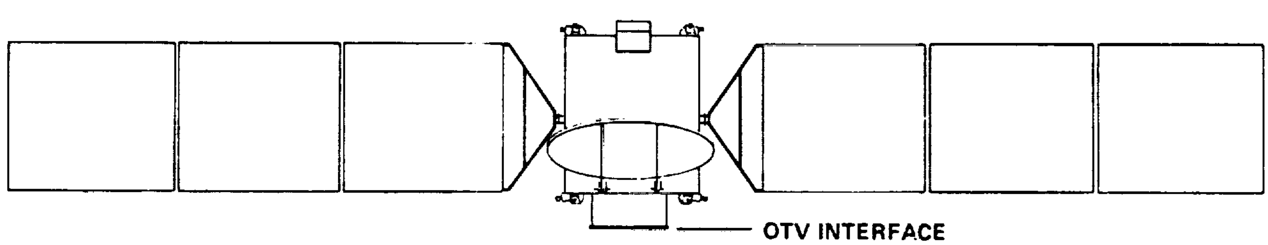


Figure VI–10: Ford FS-1300 Satellite – Deployed

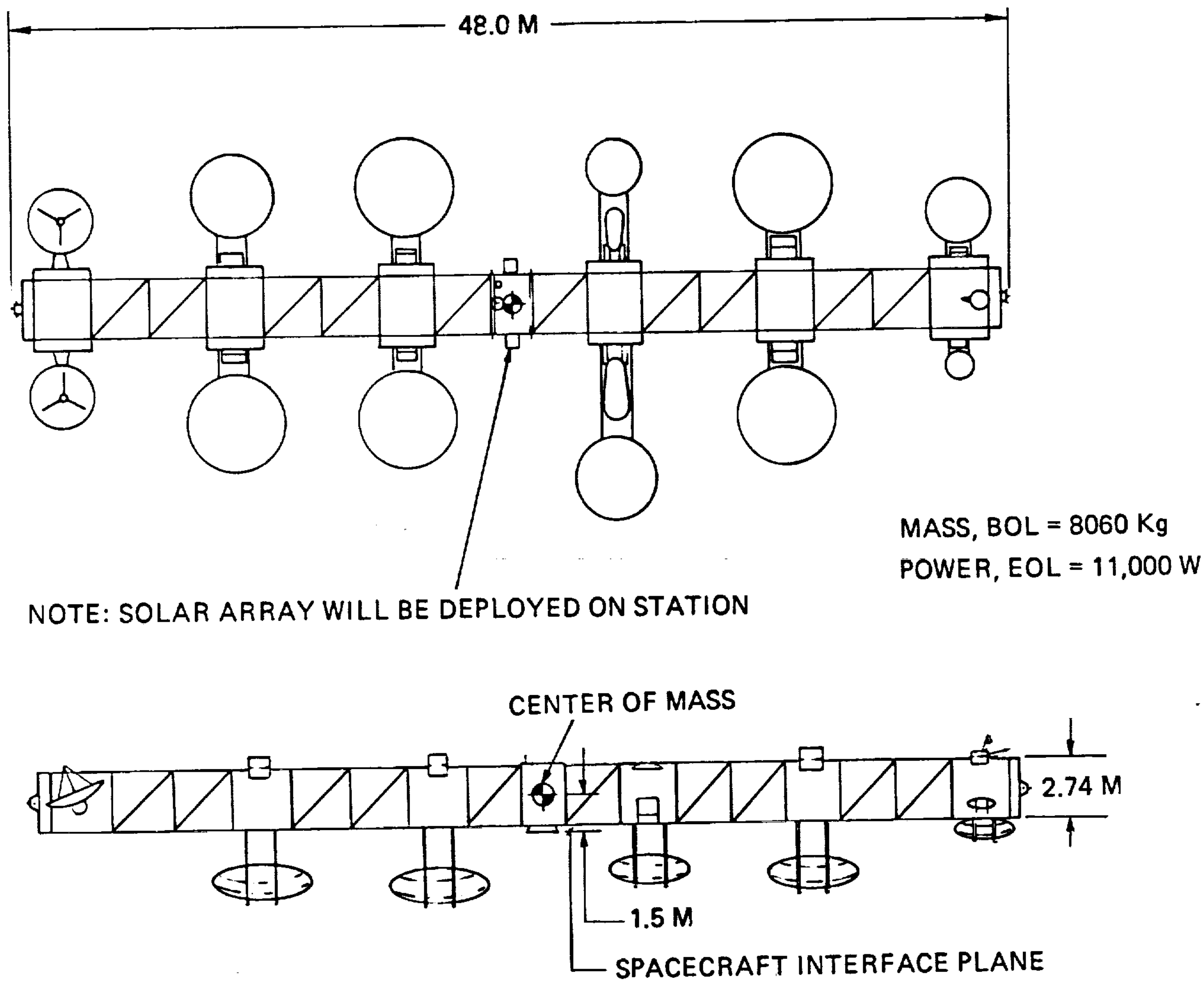


Figure VI–11: Large Geostationary Orbit Platform with Communications Payload

Section VII
CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations are given for Tasks 5, 6, and 7 as analyzed in this Supplementary Technical Report:

Task 5. Satellite Retrievability

Task 6. Impact of the Use of ELVs

Task 7. On-Orbit Assembly and Servicing

Task 8, Precursor OTV – Communications Satellite Interface Requirements, provided information to General Dynamics Corporation as reported in Section VI and did not result in conclusions or recommendations.

1 Satellite Retrievability

This subsection presents the results of the Task 5 Satellite Retrievability study of Section III.

1.1 New Modeling Results

A major result is that use of the DOMSAT III financial model which explicitly considers satellite system reliability reveals greater benefits for use of the Space Station in the launch of commercial communications satellites. Not only is return-on-investment improved (16.3% vs 9.9%), but also financial risk (defined as the standard deviation of the return-on-investment) is reduced (1.7% vs 4.8%)

The comparison is between launch of a 3-axis, Ku-band satellite using a Space Station scenario (deployment of appendages, checkout, and use of OTV for transport to GEO) and launch of the same satellite direct from earth to GEO.

A new dimension to the economic performance tradeoffs is allowed by the computation of the financial risk. The calculation is possible since DOMSAT is a Monte Carlo model which runs 1,000 cases for each scenario, with random choices at each decision point being made based on input reliabilities. Thus not only can the average (expected) return-on-investment be calculated, but the probability distribution of the return-on-investment can also be determined.

For the baseline non-Station scenario, the expected return-on-investment is 9.9% with a standard deviation of 4.8%. This means there is a .67 probability that the return-on-investment will lie between 5.1% and 14.7% – an uncomfortably large range!

For the baseline Station scenario, the expected return-on-investment is 16.3% with a standard deviation of 1.7%. The financial backers of the satellite will be much happier with a return-on-investment of 14.6% to 18%, not only because it is higher but the range of variation is smaller.

The financial risk is lower for the Space Station scenario because of the greater overall reliability achieved by use of the Space Station, in particular the greater reliability of the space-based OTV launch versus the solid rocket upper stages of the ELV.

1.2 Retrieval/Repair Results

In-orbit, at the Space Station, and return-to-earth repair scenarios are analyzed with the DOMSAT model, with the result that there is no improvement in economic performance (increased return or reduced risk) for these scenarios.

General scenarios covering all possible recoverable/repairable failures during the life of a satellite system are considered. The negative result means that in general, space retrieval operations are not financially viable for commercial communications satellites.

However, specific cases may still be attractive to retrieve. These cases include "easy" retrievals where the probability of success is high and cost of retrieval is low, and high value or time-critical payloads. Thus while retrieval/repair operations are judged to be infrequent, NASA should make sure a capability for retrieval and repair is available at the Space Station.

It is recommended that additional sensitivity analyses be performed to establish the general conditions for which retrieval of communications satellites is cost effective. In particular, different business scenarios should be analyzed and the financial impacts established for variations in reliability as well as cost of transportation systems and satellites.

1.3 Impact of Insurance

1.3.1 DOMSAT Model Results

Comparison of no insurance and insurance options shows that buying insurance acts to reduce financial risk, typically by 1 point in the return-on-investment. There is also a decrease in return-on-investment, typically 1 point for the Space Station scenarios but as much as 5 points for the riskier non-Station scenarios.

Modeling of the effects of changes in insurance rates show how expected return-on-investment slowly decreases with increasing rates. The financial risk changes very little with change in insurance rate for the Station scenarios. However, for the less reliable non-Station scenarios there is a rapid increase in risk as the insurance rate increases. Self insurance appears to be the only viable option for non-Station scenarios if the insurance multiplier is larger than 1.25 (i.e. the insurance rate is more than 25% higher than the loss rate).

1.3.2 Insurance Industry Interviews

The insurance industry sees no possibility of rate reductions for new space operations that are claimed to be more reliable until they have been demonstrated. In fact, the opposite in terms of rate increases is likely to occur. Thus it becomes important for NASA to demonstrate the value and safety of new space activities on demonstration missions and initial use with government satellites. Ultimately composite rates for satellite launches can be expected to approach the 10% range (from the present day 20% based on historical failure data).

An equally important point is the expected increase in insurance capacity as transportation between the earth and Space Station becomes a more routine matter with cargo manifested and satellite components perhaps spread among several loads.

1.4 Impact of Launch Costs

Launch costs directly influence ROI for all cases. The Station scenarios are more sensitive to upper stage (OTV) costs while the non-Station scenarios are more influenced by the initial stage (or Shuttle) launch costs. Non-Station scenario risk varies rapidly with changes in launch costs.

1.5 Requirements on Space Station

Physical requirements are the same as recommended in the original study technical report. However, the provision for OTV docking with a free satellite undergoing retrieval would greatly increase the flexibility of retrieval operations. This would require a delicate maneuvering capability as well as cold gas thrusters to avoid damage to the satellite.

Operational requirements should emphasize reduction in paper work and the fact that time is money for commercial operations. NASA control of the satellite should be kept to the minimum required by safety and security.

2 Impact of ELVs

This subsection presents the results of the Task 6 Impact of ELVs study of Section IV.

2.1 Impact on APOs

Cost analysis shows that using ELVs in place of the Shuttle changes launch costs, but does not change the value of the APOs when comparing business-as-usual ELV delivery with ELV Space Station delivery.

2.2 Spreading of Launch Risk

Launching multiple support vehicles on a regular basis offers the satellite industry with a method of spreading the launch risk over several launches and assembling the satellite at the Space Station. This may eventually drive insurance costs down, increasing the values of the assembly APOs.

2.3 Need for ELVs to Support Space Station

An ELV system is needed to support the Space Station. It is the recommendation of this study that an additional set of studies be developed and followed through by NASA, or that existing studies be given specific scope to examine the use of a specialized ELV Space Station support system that minimizes work load on the Space Station crew.

The system we have developed consists of a mid-sized ELV system with a payload carrier of sufficient size for two common-sized satellites without upper stages. This system could be derived from an existing ELV design to defray design costs. A reusable guidance, navigation and docking system would be attached to several predesigned carriers. This system would probably use a dual propellant system, a mono or dual propellant system to deliver the payload from a safe ELV launch distance to the Station area, and a cold gas system to provide the final maneuvering and docking within the Space Station safety envelope.

The maneuvering and docking system should be designed to be a man-rated safe system that can perform all its functions automatically. A Space Station override should be included as an added safety feature. The maneuvering and docking system would be removed at the Station with the exception of a small, low-cost, disposable system that would take the carrier and any Space Station waste into an orbit where it could enter and burn in the atmosphere. The higher-cost, maneuvering and docking system can be returned on the Space Shuttle with other Space Station items.

This is a system that can be proven early and can solve issues dealing with liability because the ELV system could be controlled by NASA (being a single system) and eliminate the multiple transfers that would be required with an OMV scenario. The use of ELVs would provide NASA with a system that can easily accommodate small schedule upsets because no turnaround is needed (by having several maneuvering and docking systems in use).

The use of such a system can provide almost unlimited Station support, does not put a high load on the crew, and provides a regular waste disposal system for the Station, opening up additional STS return capability for the ELV docking and maneuvering system and other returnable items. Payloads, as well as hard and soft resupplies can be delivered to the Station on a regular basis as well as allowing short term, high frequency support (many payloads over a few days) that could prepare the Station for a long duration confinement period for long lasting low-g experiments.

The launch capability of the Shuttle can then be dedicated to crew changes and large payloads which are more infrequent, reducing the launch load on the Shuttle fleet, extending the life of each vehicle, and providing a system that is not dependent on only one launch system that could be grounded due to a failure or long, unexpected launch delays.

3 Assembly and Servicing

This subsection presents the results of the Task 7 Assembly and Servicing study of Section V. Servicing offers improved economic performance provided that the satellite development and transportation costs are not greatly affected. However, servicing has the effect of reducing the payload fraction (the mass of the payload versus the dry mass of the satellite) which in turn diminishes revenue generating capacity. It is recommended that the serviceable designs be given further study with respect to these factors.

3.1 Space Station Infrastructure

The planned NASA infrastructure – transportation systems, Space Station facilities, and remote servicing systems – is assessed to determine the feasibility of on-orbit assembly and servicing and to determine any design drivers for future satellites. The following conclusions are reached:

- The planned Space Station infrastructure will support on-orbit assembly and servicing.
- The Integrated Orbital Servicing System should be considered for the first generation remote servicing system.
- The Orbital Spacecraft Consumables Resupply System is too large for commercial satellite servicing applications. A smaller refueling kit or OMV scavenging system should be developed.

3.2 Serviceable Satellites

The current trend in satellite manufacture is towards modularity. Modularity allows the assembly and test activities for the various subsystems to be performed in parallel and integrated as complete assemblies. As satellites become completely modular, they can be assembled on orbit at the Space Station and serviced remotely. In order to determine the benefits of servicing, three modular satellite designs are developed:

1. The **Refuelable Satellite Design** is a slight modification to the baseline business-as-usual satellite that can be launched by ELV directly to GEO orbit. It is capable of being refueled in orbit using the OMV, OTV, and remote servicer. The decreased fuel mass allows the satellite to accommodate a greater number of transponders.
2. The **Closed Architecture Design** is capable of being deployed and tested at the Space Station and serviced on orbit after an initial 12 year lifetime. It is capable of undergoing refueling and replacement of life-limited payload equipment with the exception of solar arrays.
3. The **Open Architecture Design** is capable of being transported to LEO in pieces, assembled and tested at the Space Station, and serviced on orbit after an initial 12 year lifetime. It is capable of undergoing refueling and replacement of life-limited payload equipment with the exception of solar arrays. In addition it is capable of on-orbit storage of degraded or failed orbital replacement units.

The following conclusions about serviceable satellites are reached:

- The major factor that limits the lifetimes of most GEO satellites is radiation degradation. Improvements in radiation hardening techniques for electrical components, composites, and solar cells should be researched.
- Solar array degradation becomes a major design driver. Improvements in solar cell technology will be required. Gallium arsenide and indium phosphide cells which are more resistant to radiation should be developed.
- Spacecraft can be easily scarred for remote assembly and servicing.
- Serviceability imposes a 16% to 32% increase in the satellite dry mass.
- Modularity reduces the integration and test costs by approximately 10%.

3.3 On Orbit Assembly

Scenarios were developed for the Open and Closed architecture designs ranging from deployment of appendages to subsystem level assembly. Following assembly and test operations, the Space Based Orbital Transfer Vehicle (SB-OTV) is used to transport the satellite to GEO. The following conclusions regarding on-orbit assembly are reached:

- On orbit assembly can be accomplished with the planned NASA infrastructure.
- Assembly at the Space Station reduces the risk of launch failures and consequently should result in lower insurance costs.

- The SB-OTV reduces the launch costs by 16%.
- "Space available" launch scenarios should be evaluated as a means of reducing transportation costs. These scenarios encourage complete utilization of launch vehicle capacity and allow launch costs to be spread among several users.

3.4 On Orbit Servicing

Servicing scenarios are developed for the refuelable, open architecture and closed architecture designs. The servicing scenarios ranged from on-orbit refueling to subsystem level replacement. The following conclusions regarding on-orbit servicing are reached:

- Satellite servicing can be performed in-situ with a simple robotic servicer.
- Not all subsystems can be serviced with current technology. The level of servicing is, however, sufficient to restore the satellite to original condition.
- On orbit servicing can be performed for 30% less than complete replacement.
- Space debris is an issue that requires further study.

3.5 Economic Performance

The economic performance of the serviceable designs is evaluated and compared to the baseline with the following results:

- The serviceable designs give greater internal rates of return (IRR) and higher net present value (NPV) than the baseline design.
- The refuelable design offered the best performance followed by the closed and open architectures respectively. Tables VII-1 and VII-2 summarize the improvement in economic performance of the serviceable designs compared to the baseline satellite designs.

	Mission Life (yr)		
Satellite Design	12	14	24
Refuelable (ELV launch)	6.7	7.7	–
Refuelable (OTV launch)	8.6	9.8	–
Open Architecture	–	–	3.5
Closed Architecture	–	–	6.0

Table VII–1: Improvement in Return (%)

	Mission Life (yr)		
Satellite Design	12	14	24
Refuelable (ELV launch)	19.2	23.9	–
Refuelable (OTV launch)	20.3	24.4	–
Open Architecture	–	–	21.8
Closed Architecture	–	–	21.4

Table VII–2: Improvement in NPV ($M)

- The economic benefit of servicing is strongly correlated with initial capital expenditures and payload mass fraction. Serviceable designs must continue to efficiently use available mass and power.

3.6 Space Station Impacts

On orbit assembly and servicing can be supported by the Phase II Space Station. In order to reduce the impact of these activities on the Space Station, the following changes are recommended:

- At least one OMV should be added to the fleet to allow for extended remote operations.
- The fueling platforms should have their own dedicated robotic systems for automated fueling.
- Space Station insurance issues require further study. More information is needed to determine the effect of the Space Station on insurance rates.

3.7 NASA Course of Action

It is recommended that NASA take the following actions to encourage commercial satellite users and manufacturers to build serviceable satellites:

- Pricing policies should be developed to encourage commercial users to utilize the Space Station facilities in the most efficient manner.
- Preliminary prices should be published that allow commercial users to estimate the cost of on-orbit assembly and servicing.

Appendix A
SATELLITE FAILURE DATABASE

Type of Failure	Percentages: Failed launches	Percentages: All launches
Initial launch stage	11.8	2.0
Upper launch stages	29.4	5.1
Apogee kick motor	29.4	5.1
Sat. before checkout	11.8	2.0
Sat. after checkout	17.6	3.1
Totals	100.0	17.3

Table A–1: Historical Failure Statistics

1 Satellite Failures

Historical incidents of satellite failure for geosynchronous communications satellites are classified into five categories:

1. Initial launch stage
2. Upper launch stages
3. Apogee kick motor
4. Satellite before initial operation
5. Satellite after initial operation

Table A-1 gives the breakdown of geosynchronous communications satellite failures for the last ten years based on the data in Table A-3 (17 failures out of 98 attempts). Data is restricted to satellites of United States and Western European manufacture due the unreliability of information on Soviet launches. Experimental, meteorological, or scientific satellites are not in this breakdown.

Table A-2 gives geosynchronous communication satellite failures by category for the years 1963 through 1976. Table A-3 gives geosynchronous communication satellite failures by category for the years 1977 through 1986. Since the *Challenger* STS failure on 28 January 1986 and the Ariane failure on 30 May 1986, there have been no attempts to launch commercial communication satellites.

The 1977 through 1986 time period is used to generate failure statistics and draw conclusions on the value of retrieval and repair operations. In this period there were 17 failures of communications satellites out of 98 launch attempts for a 17% failure rate. (This rate does not necessarily correspond with insurance rates which are determined by the loss ratio and the failure statistics for all satellites using the particular launch vehicle.)

Table A-4 gives the cause of failure for the geosynchronous communication satellite failures during the 1977 through 1986 time period. The " * " under cause of failure indicates a partial mission loss.

There are too many cases to tabulate of degraded performance of the satellite. This information tends to be tightly held and not released for general publication. However, significant "life insurance" claims are paid against claims of degraded performance.

2 Launch Attempts

Tables A-7 through A-10 give all geosynchronous satellite launches for the years 1977 through 1986, and part of 1987. (There were very few launches in 1986/1987 due to engineering problems with the Shuttle and Ariane.) Satellite names, country of origin (if non-USA), and government agency responsible for the satellite op-

Satellite Failures			Failure Category				
Launch Date	Satellite	Launcher	1	2	3	4	5
12 Feb 1963	Syncom 1	Thor Delta			*		
26 Oct 1966	Intelsat II	Delta			*		
6 Apr 1967	ATS 2	Atlas Agena		*			
10 Aug 1968	ATS 4	Atlas Centaur		*			
19 Sep 1968	Intelsat III-1	Delta	*				
26 Jul 1969	Intelsat III-5	Delta		*			
12 Aug 1969	ATS 5	Atlas Centaur				*	
23 Jul 1970	Intelsat III-8	Delta			*		
19 Aug 1970	Skynet 2	Delta			*		
18 Jan 1974	Skynet 2A	Delta	*				
20 Feb 1975	Intelsat IV-6	Atlas Centaur	*				
		Totals	3	3	4	1	0

Table A–2: Geosynchronous Communication Satellite Failures by Category (1963 – 1976)

Satellite Failures			Failure Category					Totals	
Launch Date	Satellite (fail date)	Launcher	1	2	3	4	5	Fail	Attempt
29 Sep 1977	Intelsat IVA-5	Altas Centaur	*						
6 Dec 1979	Satcom 3	Delta 3914			*				
10 Apr 1982	Insat 1A	Delta 3910, PAM				*			
15 Sep 1982	Marecs B	Ariane 1 - L5		*					
4 Apr 1983	TDRS A	STS, IUS			*				
4 Feb 1984	Westar 6	STS 41B, PAM D			*				
6 Feb 1984	Palapa B2	STS 41B, PAM D			*				
9 Jun 1984	Intelsat V-9	Atlas Centaur		*					
9 Nov 1984	Anik D2 (4/29/85)	STS, PAM D					*		
31 Aug 1984	Leasat 2 (9/25/85)	STS, Minuteman					*		
8 Feb 1985	Arabsat 1A	Ariane 3					*		
12 Apr 1985	Leasat 3	STS, 51D			*				
29 Aug 1985	Leasat 4	STS, 51I				*			
12 Sep 1985	ECS 3	Ariane 3, V15		*					
12 Sep 1985	Spacenet 3	Ariane 3, V15		*					
28 Jan 1986	TDRS B	STS, 51L	*						
30 May 1986	Intelsat V-14	Ariane 2		*					
		Totals	2	5	5	2	3	17	98

Table A–3: Geosynchronous Communication Satellite Failures by Category (1977 – 1986)

Launch Date	Satellite (fail date)	Failure Category	Cause of Failure (* = partial mission loss)
? ? 1976	Satcom 2 (4/83)	5	* 12/24 transponders failed after seven years
13 Sep 1977	OTS 1	1	Delta vehicle failure
29 Sep 1977	Intelsat IVA-5	1	Atlas booster failure
6 Feb 1979	Ayame 1	2	Final stage collision with satellite, subnominal orbit
6 Dec 1979	RCA Satcom 3	3	Apogee motor failure, subnominal orbit
22 Feb 1980	Ayame 2	3	Apogee motor failure
10 Apr 1982	Insat 1A	4	Sensor problem, stationkeeping fuel exhausted
15 Sep 1982	Marecs B	2	Ariane third stage failure, falls into Atlantic
15 Sep 1982	Sirio 2	2	Ariane third stage failure, falls into Atlantic
4 Apr 1983	TDRS A	3	* Upper stage failure, station fuel used to reach orbit
4 Feb 1984	Westar 6	3	Pam D failure, STS rescue 11/84 and return to earth
6 Feb 1984	Palapa B2	3	Pam D failure, STS rescue 11/84 and return to earth
9 Jun 1984	Intelsat V-9	2	Centaur stage failure, fails to reach orbit
9 Nov 1984	Anik D2 (4/29/85)	5	* Antenna pointing failure, loses earth lock, use of fuel to regain control greatly shortens life.
8 Feb 1985	Arabsat 1A	5	* Attitude control failure, satellite operated manually
12 Apr 1985	Leasat 3	3	* IUS fails, STS mission 8/85 activates perigee stage, satellite reaches orbit OK.
29 Aug 1985	Leasat 4	4	Deployment failure.
31 Aug 1984	Leasat 2 (9/25/85)	5	Total failure, cause unknown.
12 Sep 1985	ECS 3	2	Ariane third stage fails to ignite, vehicle blown up.
12 Sep 1985	Spacenet 3	2	Ariane third stage fails to ignite, vehicle blown up.
28 Jan 1986	TDRS B	1	Shuttle booster rocket failure, destroyed by explosion.
30 May 1986	Intelsat V-14	2	Ariane third stage engine failure, vehicle blown up.

Table A–4: Cause of Failures for Geosynchronous Communication Satellites (1977 – 1986) eration (if USA) are given. The International Number designation for the object in space is given for those satellites that reached orbit. The launch date is also given, and the "Fail?" column indicates if the satellite failed during launch or in orbit. (Table A-4 has given details of the communication satellite failures.)

The satellite "type codes" are as follows:

C = Communications satellite

S = Scientific mission

M = Meteorological satellite

X = Experimental satellite

G = Government or military

A single satellite can be several types simultaneous. For example, INSAT carries both communications and meteorological payloads. Also there are a significant number of government communications satellites in geosynchronous orbits. (Geosynchronous orbits include geostationary orbits. There are several government, experimental, and meteorological satellites in geosynchronous but not geostationary orbits.)

Table A-5 gives the number of satellite failures for each satellite type for launches in the 1977 through 1986 time period. Table A-6 gives totals for the different categories of satellites launched by year for 1977 through 1986. The primary purpose of the satellite is picked so the totals accurately reflect the total number of intended geostationary satellites launched during the year. Any experimental satellite is classified as such. Satellites with communications plus other payloads (except experimental) are classified as "communications". An additional category "Government" indicates how many satellites of the "Total" belong to United States government agencies.

Satellite Type	Number Failures	Number Attempts
C	17	98
S	1	3
M	0	9
X	3	11
	21	121
G	3	21

Table A–5: Failures by Satellite Type

Satellite Category	Year of Launch										Totals
	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	
Communications	6	8	5	4	7	11	13	17	22	5	98
Scientific	1	2	–	–	–	–	–	–	–	–	3
Meteorological	3	1	–	1	3	–	1	–	–	–	9
Experimental	4	2	1	1	2	1	–	–	–	–	11
Totals	14	13	6	6	12	12	14	17	22	5	121
Government (of total)	3	3	3	2	2	–	2	2	3	1	21
Failures (of total)	3	0	2	0	0	3	1	5	5	2	21

Table A–6: Geosynchronous Satellite Summary: 1977 – 1986

Satellite [Country/Agency]	International Number	Launch Date	Fail?	Type Codes C	S	M	X	G
NATO-3 B	1977 5-A	28 Jan		C				G
ETS-2 (Kiku-2) [Japan]	1977-14-A	23 Feb			S		X	
Palapa-A2 [Indonesia]	1977-18-A	10 Mar		C				
ESA-GEOS-1	1977-29-A	20 Apr	fail		S			
DSCS-11 7	1977-34-A	12 May		C				G
DSCS-11 8	1977-34-B	12 May		C				G
Intelsat-IVA F4	1977-41-A	26 May		C				
GOES-2 [NOAA]	1977-48-A	16 Jun				M		
GMS-1 (Himawari-1) [Japan]	1977-65-A	14 Jul				M		
Sirio [Italy]	1977-80-A	25 Aug		C			X	
OTS 1 [ESA]	(no orbit)	13 Sep	fail	C			X	
Intelsat-IVA F5	(no orbit)	29 Sep	fail	C				
Meteosat-1 [ESA]	1977-108-A	23 Nov				M		
CS (Sakura) [Japan]	1977-118-A	15 Dec		C			X	
Intelsat-IV A F3	1978-2-A	10 Jan		C				
IUE-1	1978-12-A	26 Jan			S			
FLTSATCOM-1	1978-16-A	9 Feb		C		M		
Intelsat-IV A F6	1978-35-A	31 Mar		C				
BSE [Japan]	1978-39-A	7 Apr		C			X	
OTS-2 [ESA]	1978-44-A	11 May		C			X	
GOES-3 [NOAA]	1978-62-A	16 Jun				M		
Comstar-3	1978-68-A	29 Jun		C				
ESA-GEOS-2	1978-71-A	14 Jul			S			G
NATO-3 C	1978-106-A	19 Nov		C				G
DSCS-II 9	1978-113-A	13 Dec		C				G
DSCS-11 10	1978-113-B	13 Dec		C				
Anik-B1 [Canada]	1978-116-A	16 Dec		C				
Ayame-1 [Japan]	1979-9-A	6 Feb	fail	C			X	
FLTSATCOM-2	1979-38-A	4 May		C				G
Westar-3	1979-72-A	10 Aug		C				
DSCS-11 13	1979-98-A	21 Nov		C				G
DSCS-11 14	1979-98-B	21 Nov		C				G
RCA-Satcom-3	1979-101-A	7 Dec	fail	C				
FLTSATCOM-3	1980-4-A	18 Jan		C				G
Ayame-2 [Japan]	1980-18-A	22 Feb		C			X	
GOES-4 [NOAA]	1980-74-A	9 Sep				M		
FLTSATCOM-4	1980-87-A	31 Oct		C				G
SBS-1	1980-91-A	15 Nov		C				
Intelsat-V F2	1980-98-A	6 Dec		C				

Table A–7: Geosynchronous Satellite Launches, 1977 – 1980

Satellite [Country/Agency]	International Number	Launch Date	Fail?	Type Codes C	S	M	X	G
ETS-4 (Kiku-3) [Japan]	1981-12-A	11 Feb					X	
Comstar-4	1981-18-A	21 Feb		C				
GOES-5	1981-49-A	22 May				M	G	
Intelsat-V F1	1981-50-A	23 May		C				
Meteosat-2 [ESA]	1981-57-A	19 Jun				M		
Apple [India]	1981-57-B	19 Jun		C			X	
FLTSATCOM-5	1981-73-A	6 Aug		C				G
GMS-2 (Mimawari-2) [Japan]	1981-76-A	11 Aug				M		
SBS-2	1981-96-A	24 Sep		C				
RCA-Satcom-3R	1981-114-A	20 Nov		C				
Intelsat-V F3	1981-119-A	15 Dec		C				
Marecs-1 [ESA]	1981-122-A	20 Dec		C				
RCA-Satcom-4	1982-4-A	16 Jan		C				
Westar-4	1982-14-A	26 Feb		C				
Intelsat-V F4	1982-17-A	5 Mar		C				
Insat-1A [India]	1982-31-A	10 Apr	fail	C		M		
Westar-5	1982-58-A	9 Jun		C				
Anik-D1 [Canada]	1982-82-A	26 Aug		C				
Marecs B	(no orbit)	15 Sep	fail	C				
Sirio 2 [Italy]	(no orbit)	15 Sep	fail	C			X	
Intelsat-V F5	1982-97-A	28 Sep		C				
RCA-Satcom-5 (Aurora 1)	1982-105-A	28 Oct		C				
SBS-3	1982-110-B	11 Nov		C				
Anik-C3 [Canada]	1982-110-C	12 Nov		C				
CS-2A (Sakura) [Japan]	1983-6-A	4 Feb		C				
TDRS-1	1983-26-B	5 Apr	fail	C			G	
RCA-Satcom-6 (1R)	1983-30-A	11 Apr		C				
GOES-6 [NOAA]	1983-41-A	28 Apr				M	G	
Intelsat-V F6	1983-47-A	19 May		C				
ECS-1 (Eutelsat-F1) [ESA]	1983-58-A	16 Jun		C				
Anik-C2 [Canada]	1983-59-B	18 Jun		C				
Galaxy-1	1983-65-A	28 Jun		C				
Telstar-301	1983-77-A	28 Jul		C				
CS-2B(Sakura) [Japan]	1983-81-A	5 Aug		C				
Insat-1B [India]	1983-89-B	31 Aug		C		M		
RCA-Satcom-7 (2R)	1983-94-A	8 Sep		C				
Galaxy-2	1983-98-A	22 Sep		C				
Intelsat-V F7	1983-105-A	19 Oct		C				

Table A–8: Geosynchronous Satellite Launches, 1981 – 1983

Satellite [Country/Agency]	International Number	Launch Date	Fail?	Type Codes C	S	M	X	G
BS-2A [Japan]	1984-5-A	23 Jan		C				
Westar-6	1984-11-B	3 Feb	fail	C				
Palapa-B2 [Indonesia]	1984-11-D	6 Feb	fail	C				
Intelsat-V F8	1984-23-A	5 Mar		C				
Spacenet-1	1984-49-A	22 May		C				
Intelsat-V F9	1984-57-A	9 Jun	fail	C				
Eutelsat-1 F2 (ECS-2) [Europe]	1984-81-A	4 Aug		C				
Telecom-1A [France]	1984-81-B	4 Aug		C				
SBS-4	1984-93-B	30 Aug		C				
Syncom-42 (Leasat-2)	1984-93-C	31 Aug	fail	C		M		
Telstar-302	1984-93-D	1 Sep		C				
Galaxy-3	1984-101-A	21 Sep		C				
Anik-D2 [Canada]	1984-113-B	9 Nov	fail	C				
Syncom-41 (Leasat-1)	1984-113-C	10 Nov		C				G
Spacenet-2	1984-114-A	10 Nov		C				
Marecs-2 [Europe]	1984-114-B	10 Nov		C				
NATO-3D	1984-115-A	14 Nov		C				G
Arabsat-1A [Arab States]	1985-15-A	8 Feb	fail	C				
SBTS-1 [Brazil]	1985-15-B	8 Feb		C				
Intelsat-5 F10	1985-25-A	22 Mar		C				
Anik-C1 (Telesat) [Canada]	1985-28-B	13 Apr		C				
Syncom-4 (Leasat 3)	1985-28-C	12 Apr	fail	C				
Gstar-1A	1985-35-A	8 May		C				
Telecom-1B [France]	1985-35-B	8 May		C				
Morelos-1 [Mexico]	1985-48-B	17 Jun		C				
Arabsat-1B [Arab States]	1985-48-C	18 Jun		C				
Telstar-303	1985-48-D	19 Jun		C				
Intelsat-5A F11	1985-55-A	30 Jun		C				
Spacenet 3	(no orbit)	1 Aug	fail	C				
Aussat-1 [Australia]	1985-76-B	27 Aug		C				
ASC-1	1985-76-C	27 Aug		C				
Syncom-4 (4) (Leasat 4)	1985-76-D	29 Aug	fail	C				G
ECS-3 [Japan]	(no orbit)	12 Sep	fail	C				
Intelsat-5A F12	1985-87-A	28 Sep		C				
USA-11 (DSCS III type)	1985-92-B	3 Oct		C				G
USA-12 (DSCS III type)	1985-92-C	3 Oct		C				G
Morelos-2 [Mexico]	1985-109-B	27 Nov		C				
Aussat-2 [Australia]	1985-109-C	27 Nov		C				
Satcom-K2	1985-109-D	28 Nov		C				

Table A–9: Geosynchronous Satellite Launches, 1984 – 1985

Satellite [Country/Agency]	International Number	Launch Date	Fail?	Type Codes C	S	M	X	G
Satcom-K1	1986-??	12 Jan		C				
TDRS-B	(no orbit)	28 Jan	fail	C				G
Brazilsat S2	1986-??	29 Mar		C				
Gstar-2	1986-??	29 Mar		C				
Intelsat-5 F14	(no orbit)	30 May	fail	C				
FltSatCom F7	1986-??	4 Dec		C		M		
ECS-4 (Eutelsat I F-4) [Europe]	1987-??	16 Sep		C				
Aussat K3 [Australia]	1987-??	16 Sep		C				

Table A–10: Geosynchronous Satellite Launches, 1986 – 1987 (incomplete)

Appendix B
EXPENDABLE LAUNCH VEHICLE DATABASE

Information is presented on existing expendable launch vehicles (ELVs) in three subsections:

1. **Technical Comparison.** A listing is given of the physical characteristics of existing and proposed ELVs.

2. **Cost Comparison.** Pricing information on existing and proposed ELVs is given.

3. **Descriptions of ELVs.** A diagram and brief discussion is given for each ELV.

1 Technical Comparison

Table B-1 gives the launch capabilities of various existing and proposed ELVs. Vehicle capacities to Low Earth Orbit (LEO) and to Geosynchronous Earth Orbit (GEO) or Geosynchronous Transfer Orbit (GTO) are listed along with the size of the fairing which encloses the payload.

A variety of low earth orbits are tabulated. The United States launch vehicles generally give payload capacity to the Space Station (400 km altitude and 28.5° inclination). Arianespace launches from an equatorial site to 7° inclination orbits. A sun synchronous LEO orbit has an altitude of xxx km and $X°$ inclination.

For geosynchronous earth orbit capacity, the GEO entry under "Orbit" in Table B-1 means that the payload is placed in the GEO orbit by the ELV. The GTO entry means that the payload is placed in an elliptical orbit with apogee height at GEO (i.e. 36,000 km), and an apogee kick motor is required on the satellite to circularize its orbit.

2 Cost Comparison

Table B-2 gives a payload cost comparison chart for various ELVs. The base price is given for launch to geosynchronous transfer orbit (GTO), except for the American Rocket ILV which only provides LEO service. These prices are for use of the entire vehicle, and are composite estimates based on numerous sources. Pricing data is difficult to obtain and prices vary according to the number of launches purchased and other transaction-particular items. These prices will vary with time due to currency fluctuations for foreign launches and competitive pressures.

Also given is the cost per kilogram of payload launched to LEO and to GTO. The base price for use of the ELV is likely to be the same for a launch to low earth orbit (LEO) as to geosynchronous earth orbit (GEO) or geosynchronous transfer orbit (GTO), although more payload can be carried to LEO. The reason is that most vehicles are optimized for GEO launch and would require modification for LEO. To deliver payloads to the Space Station, some type of upper stage is required which adds back the cost of any third stage deleted from a non-GEO launch.

It is interesting to note that the average cost per kilogram to LEO is $7,540 with a standard deviation of $2,200, and the average cost per kilogram to GTO is $19,900 with a standard deviation of $5,800.

Figure B-1 gives a launch cost comparison for ELVs and the Shuttle for optimized delivery to LEO or a Space Station orbit. Cost and capacity values for the ELVs built for GTO delivery are estimated performance and cost values obtained from the ELV manufacturers. It is apparent that the ELVs built for GTO are not as competitive

Company	Vehicle	LEO Capacity Orbit	LEO Capacity (kg)	GEO Capacity Orbit	GEO Capacity (kg)	Fairing Size (m) Dia.	Fairing Size (m) Length
American Rocket	Industrial Launch Vehicle (ILV)	400 km, 28.5°	1,814	–	0	2.3	4.6
Arianespace	Ariane 3	200 km, 0°	5,800	GTO	1,390	($14\ m^3$)	
		800 km, 0°	3,450			($14\ m^3$)	
	Ariane 4	200 km, 0°	8,000	GTO	4,200	3.7	9.6
		800 km, 0°	4,500			3.7	9.6
China Great Wall Industry Corp.	Long March 2	63°	1,500	–	0	3.1	5.0
	Long March 3	Sun synch.	3,600	GTO	1,400	2.7	5.3
	Long March 2-4L	300 km	9,000	GEO	2,930	3.7	10.0
General Dynamics	Atlas G	90 km, 28.5°	6,123	GTO	2,360	2.9	8.4
	Atlas G/LPF	400 km, 28.5°	6,577	GTO	2,180	3.7	9.4
	Atlas H	400 km, 28.5°	1,996	?	?	?	?
	Atlas E	400 km, 28.5°	136	–	0	?	?
	ALV	400 km, 28.5°	45,360	?	?	?	?
Japan	H-2	400 km, 28.5°	8,000	GEO	2,000	3.7	12.0
Martin Marietta	Titan 3	400 km, 28.5°	14,061	GTO	5,670	?	?
	Titan 4	400 km, 28.5°	17,690	GTO	9,072	4.4	12.2
McDonnell Douglas	Delta 3920	160 km, 28.5°	3,452	GTO	1,284	2.4	?
	Delta 6920	320 km, 28.5°	3,787	GTO	1,447	2.5	4.8
	Delta 7920	320 km, 28.5°	4,246	?	?	2.5	4.8
	Enhanced Delta 2	320 km, 28.5°	4,781	GTO	1,819	2.8	6.2
		480 km, 28.5°	4,536			2.8	6.2
	Delta 2 MLV	400 km, 28.5°	5,171	GTO	1,814	?	?
Proton	D-1, SL-13	400 km, 28.5°	20,000	GTO	2,000	4.2	7.5
Space Services Inc.	Conestoga IV-1	Sun synch.	1,542	GTO	544	1.2	4.6

Table B–1: Commercial Expendable Launch Vehicle Database

Launch Vehicle	Base Price (to GTO) $M	Price per Unit Mass to LEO $/kg	to GTO $/kg
American Rocket, ILV	8	4,400	–
Arianespace, Ariane 4	80	10,000	19,000
China Great Wall, Long March 3	20	5,500	14,300
Gen. Dynamics, Atlas/Centaur G	51	8,300	21,600
Martin Marietta, Titan 4	100	5,600	11,000
McDonnell Douglas, Delta 2	37	7,100	20,400
McDonnell Douglas, Delta 6920	37	9,700	25,500
Space Services, Conestoga	15	9,700	27,500
Average Price per kilogram launched	–	7,540	19,900

Table B–2: Launch Cost Comparison for Expendable Launch Vehicles

for launching payloads to the Space Station.

Figure B-2 is a plot of the optimum ELV launch cost/kg versus maximum capacity for launches to Geosynchronous Transfer Orbit (GTO). Some examples (Titan, Shuttle) are included with currently available upper stages (Morton Thiokol Star 63F or Centaur G′) to compare the Space Station APO scenarios with business-as-usual scenarios. The cost per kilogram of these examples includes the upper stage cost. It is interesting to note the closeness in cost/kg to GTO for the three major American ELVs – Titan, Delta 2 and Atlas/Centaur. This appears to be a product of the competition among commercial launchers as opposed to the government subsidized launchers such as the Shuttle, Ariane, and Long March.

3 Descriptions of ELVs

A diagram and brief description is provided of the following ELVs:

1. American Rocket, ILV
2. Arianespace, Ariane 3 & 4
3. China Great Wall Industry, Long March
4. General Dynamics Atlas/Centaur
5. Japan, H-2
6. Martin Marietta, Titan 4
7. McDonnell Douglas, Delta
8. Proton Launch Vehicles
9. Space Services Inc., Conestoga

At this time there is insufficient information about the Advanced Launch System (ALS) (formerly the heavy lift launch vehicle) to warrent a detailed discussion. In general, it is anticipated that the ALS will be able to lift from 45,000 kg to 70,000 kg to low earth orbit (LEO) at an initial cost of $3,300/kg dropping over time to $1,300/kg.

3.1 American Rocket ILV

American Rocket will conduct three tests of the Industrial Launch Vehicle (ILV) in 1988. The ILV is a four stage vehicle designed to carry lighter payloads. Figure B-3 shows the ILV which has the following general characteristics:

- Height: 25 m
- Four-stage rocket
- Engines:
  - Vehicle uses 19 nearly identical hybrid rocket engines.

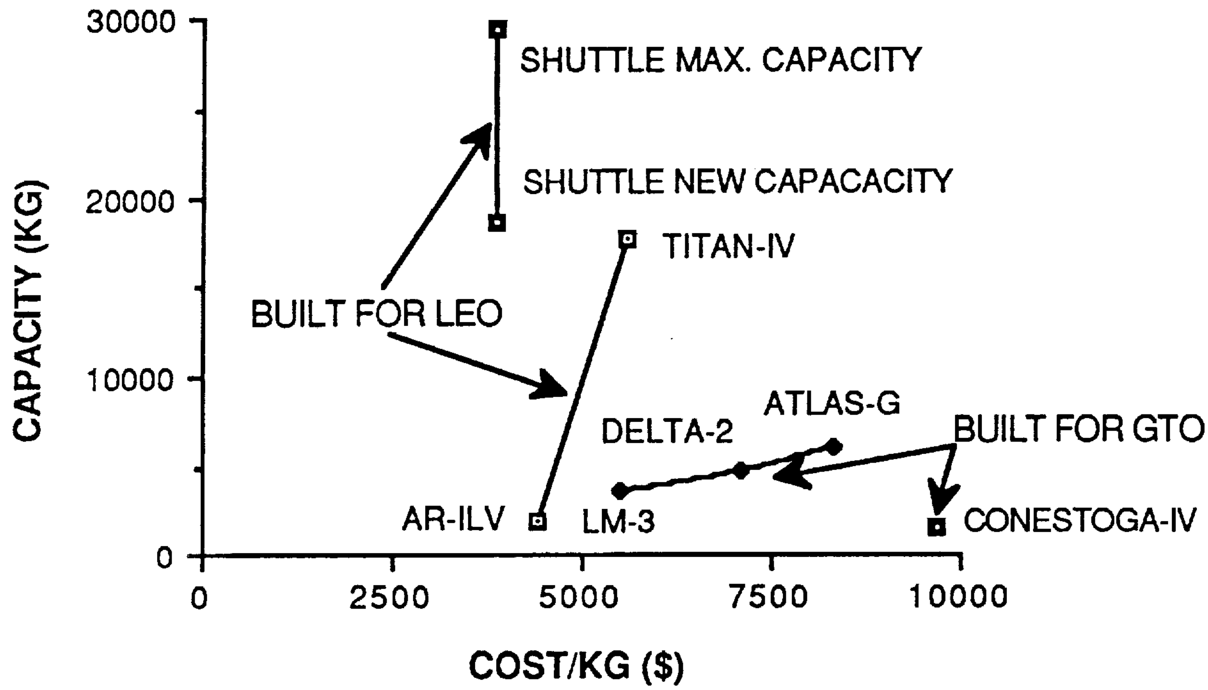


Figure B–1: Launch Cost Versus Launch Capacity (Low Earth Orbit)

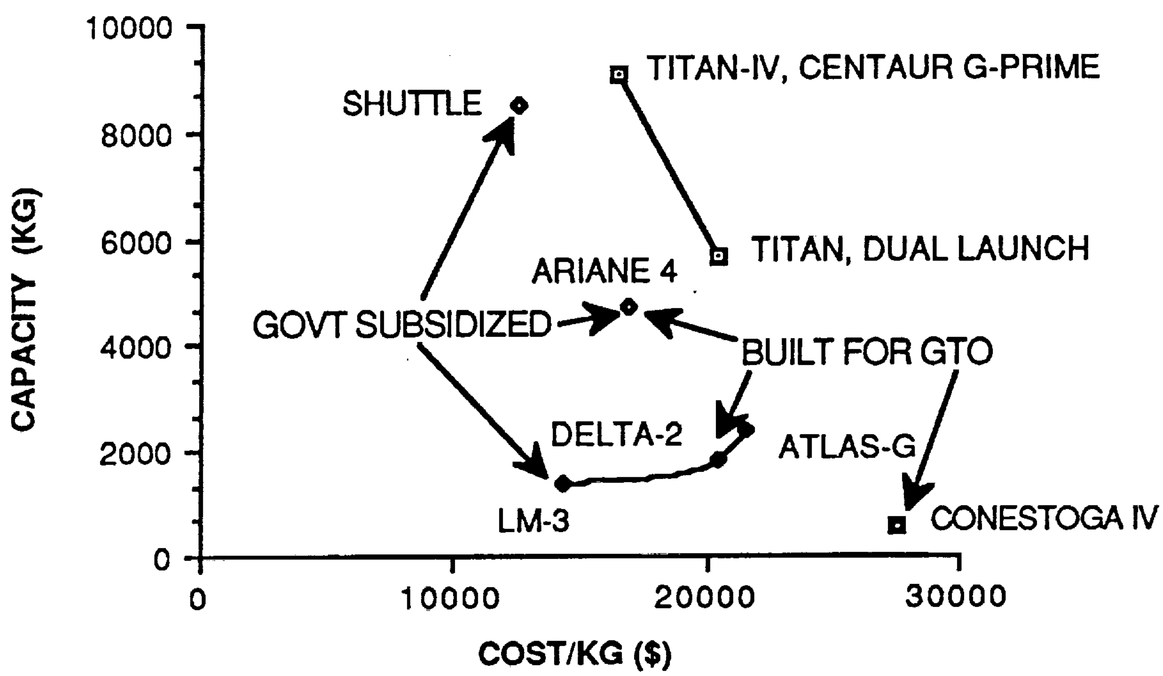


Figure B–2: Launch Cost Versus Launch Capacity (Geosynchronous Transfer Orbit)

- Stage 1: 12 hybrid motor nozzles around the base of the common oxidizer tank.
- Stages 2-4: 7 motors mounted in a hexagonal cluster above the first stage.

- Cost: $6M to $8M.

3.2 Arianespace

The Ariane rocket is a program of the European Space Agency. The Ariane 4 is a three stage vehicle propelled by liquid engines. The rocket is available in six different configurations consisting of combinations of solid and liquid strap-on boosters. Ariane rockets have been launched since 1979, and Arianespace has been responsible for the launches since 1984.

Figure B-4 shows the Ariane 4. The Ariane 3 and 4 have the following general characteristics:

Ariane 3

- Height: 49 m
- Lift-off mass: 237,000 kg
- Engines:
  - Core is the same as the Ariane 4
  - 2 to 4 strap-on boosters (solid or liquid propellants)

Ariane 4

- Height: 58.4 m
- Lift-off mass: 471,000 kg
- Engines:
  - First stage (core) consists of four Viking V liquid propellant engines.
  - Second stage consists of one Viking IV liquid propellant engine.
  - Third stage consists of one HM7 cryogenic engine.
  - Strap-on boosters are the liquid Viking VI and solids which feed the Viking VI liquid booster.

There is little specific data available for the Ariane 5. It is expected to be available in 1994 and be capable of lifting around 15,000 kg to LEO. The price of the vehicle is not yet known. The Ariane 5 will be optimized for launch to the Space Station and is intended to be the launch vehicle for the European *Columbus* module as part of the Space Station and may provide European logistics modules.

3.3 China Great Wall Industry

The first launch was the Long March 1 in 1970, and the Long March 2 was first launched in 1972. China Great Wall Industry Corporation claims a 100% success rate for eight launches. Figure B-5 shows a specification sheet for the Long March 2-4L.

Long March characteristics are summarized below:

Long March 1 (CZ-1)

- 3-stage launch vehicle
- Height: 29.5 m
- Lift-off mass: 81,600 kg
- Diameter: 2.25 m

Long March 2 (CZ-2)

- 2-stage liquid rocket
- Height: 32.6 m
- Lift-off mass: 191,000 kg
- Diameter: 3.35 m

Long March 3 (CZ-3)

- 3-stage liquid rocket
- Height: 43.3 m
- Lift-off mass: 202,000 kg
- Diameter: 3.35 m

Long March 2-4L (CZ 2-4L)

- A modified Long March 2 with stretched tanks and four liquid rocket boosters.
- The boosters are made up of the same propellants and engines as the first stage.
- Lift-off mass: 419,000 kg
- Diameter: 3.35 m

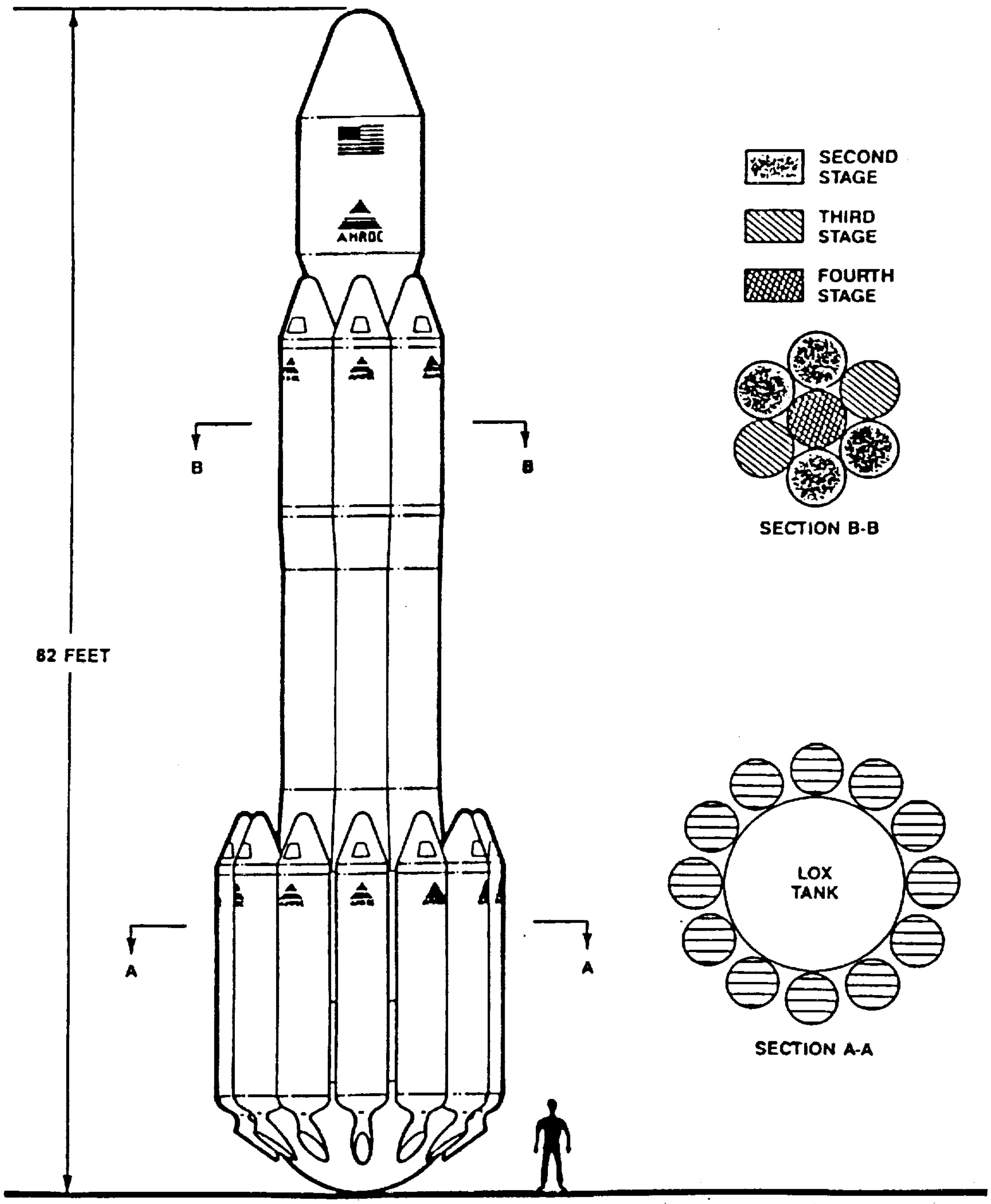
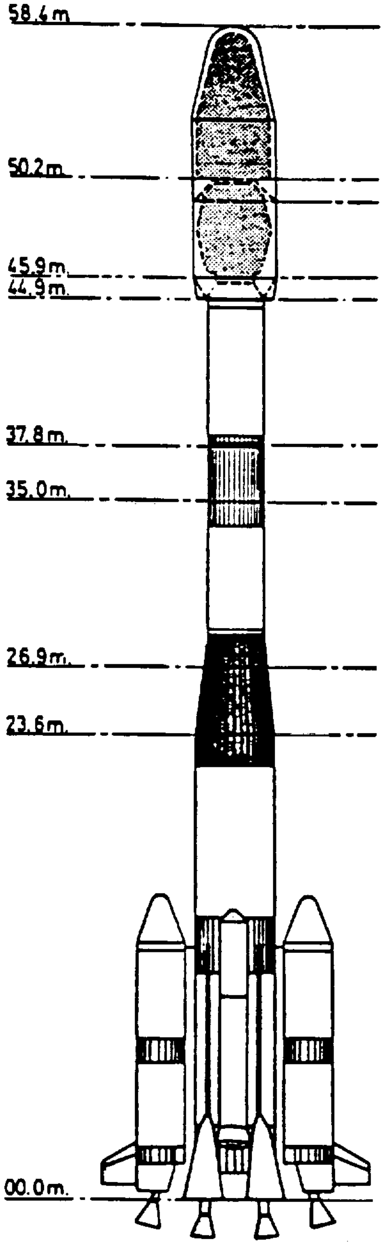


Figure B–3: American Rocket Company's Industrial Launch Vehicle



FAIRING

Supporting structure

SPELDA

V.E.B. (Vehicle Equipment Bay): The ARIANE 4 Vehicle Equipment Bay is a new concept allowing easy accessibility to the equipments without interfering with the payload compartment, either fairing or SPELDA.

Third stage: H10
10.5 metric tons cryogenic propellant.
HM7 engine - Thrust 62 KN in vacuum.
Burn time: 725 seconds.
Chamber pressure 35 bars

Interstage 2/3

Second stage: L34
34 metric tons N204 – UDMH
Viking IV engine - Thrust 786 KN in vacuum
Burn time 123 seconds.
Chamber pressure 58.5 bars

Interstage 1/2

First stage: L220
226 metric tons N204 – UDMH + Hydrate of hydrazine.
4 viking V engine - Thrust .4 x 668 KN.
Burn time 204 seconds.
Chamber pressure 58.5 bars

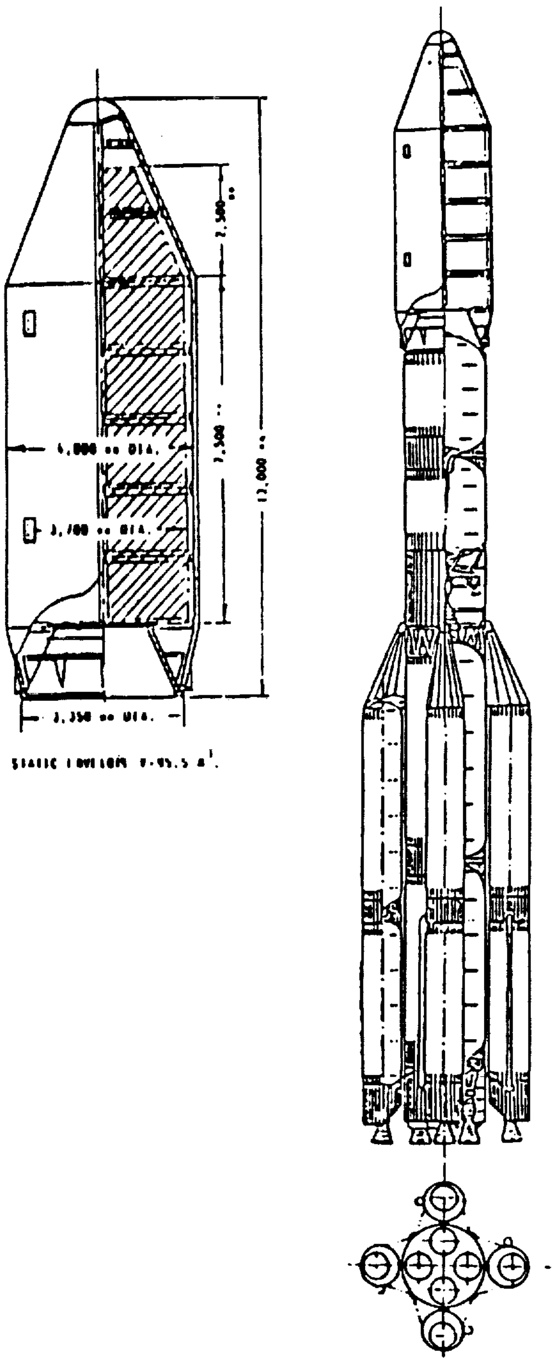
Liquid propellant strap-on booster
37 metric tons N204 + UDMH
Viking VI engines - Thrust 661 KN.
Burn time: 135 seconds.

Solid propellant strap-on booster
9.5 metric tons propellant.
Thrust: 625 KN.
Burn time 34 seconds

Inertial guidance
Due to the inertial guidance of the launch vehicle up to spacecraft separation, ARIANE 4 provides high orbit injection accuracy; typical standard deviation values are 100 km on the G.T.O. apogee, 1 km on perigee and 0.07° on inclination.

Soft flight environment
The soft flight environment allows a low spacecraft design constraint level. Same acoustics, loads, thermal and shock levels as ARIANE 2 and 3.

Figure B–4: Arianespace's Ariane 4



CZ2-4L/UPPER-STAGE GTO MISSION

* CZ2-4L: Long March 2 launch vehicle with stretched tanks and 4 liquid rocket boosters.
* Boosters: Using same propellants & engines with first stage. The boosters are fixed on first stage(non-separated)
* Upper-stage: developed for Space Shuttle. CZ2-4L will be compatible with some of Shuttle upper stages for GTO missions.
* Lift-off mass: 419,000 kg.
* Lift-off thrust: 568,000 kg.
* Maximum diameter: 3.35 m.
  Booster diameter: 1.65 m.
  Maximum width: 6.80 m.
* Fairing diameter: 4.00 m.
  Static envelope diameter: 3.70 m.
* LEO capacity: 9,000 kg.
  $H_p = H_a = 300$ km, $i = 28.5$
* Being compatible with following upper stages with their payloads for GTO launching missions: PAM-D2 PAM-A, AMS, SCOTS, HPPM & STV.
* Maximum satellite weight: (GTO)
  1,650 Kg (for AMS upper stage)
  1,900 kg (for PAM-D2 ")
  1,950 kg (for PAM-A ")
  2,400 kg (for SCOTS ")
  2,930 kg (for HPPM ")
  HS-393 communications satellite.
* Overall length: 46.50 m.

Figure B-5: China Great Wall Industry Corporation's Long March 2-4L

3.4 General Dynamics

The base Atlas/Centaur launch vehicle is a two stage rocket made up of three liquid Rocketdyne engines. General Dynamics has launches 488 vehicles in 28 years, with 95/during the last 22 years. Atlas/Centaur launches are generally made to geosynchronous orbit. Figure B-6 shows the Atlas vehicle and Centaur booster family. Figure B-7 gives the vehicle description of the Atlas Centaur.

Basic Atlas/Centaur Vehicle

- Diameter: 3 m
- Height: 42 m
- Lift-off mass: 164,000 kg (8,600 kg empty weight)
- Engines: three Rocketdyne engines fueled by liquid oxygen and kerosene.

3.5 Japan's H-II

The H-II rocket is a two stage launch vehicle using liquid oxygen and liquid hydrogen propulsion systems in both stages. The rocket is equipped with two solid rocket boosters. The rocket is being developed by the National Space Development Agency of Japan (NASDA), and is scheduled to begin flying in 1992.

Figure B-8 shows the H-II which has the following general characteristics:

- Lift off mass: 258,000 kg
- Height: 48 m
- Engines:
  - Stage 1: central core of LE-7 cryogenic engine and two solid rocket boosters.
  - Stage 2: LE-5 engine.
  - Boosters: solid rockets

3.6 Martin Marietta Titan 4

Martin Marietta has launched 136 Titan launch vehicles with a 96% success rate. Figure B-9 shows the Titan 4 (34D) which has the following general characteristics:

- Height: 61.8 m
- Engines: two seven-segment solid rocket motors
  - Stage 1: one storable liquid motor.
  - Stage 2: one storable liquid motor.
  - Centaur upper stage is cryogenic.

3.7 McDonnell Douglas Delta

Delta rockets have placed 184 satellites into orbit. The vehicle's core first stage engine is the Rocketdyne RS-27. Delta rockets generally carry their payloads into geosynchronous orbit. There is concern among potential Delta customers that their payloads will be bumped by Defense Department payloads. Figure B-10 shows the Delta 2 medium launch vehicle. Figures B-11 and B-12 show shows the Delta 2 fairing dimensions.

Delta 3920

- Engines: strap-on boosters are Castor IV solids.

Delta 6920

- Engines: strap-on boosters are Castor IVA solids. Stage 3 is a SGS II derivative.

Delta 7920

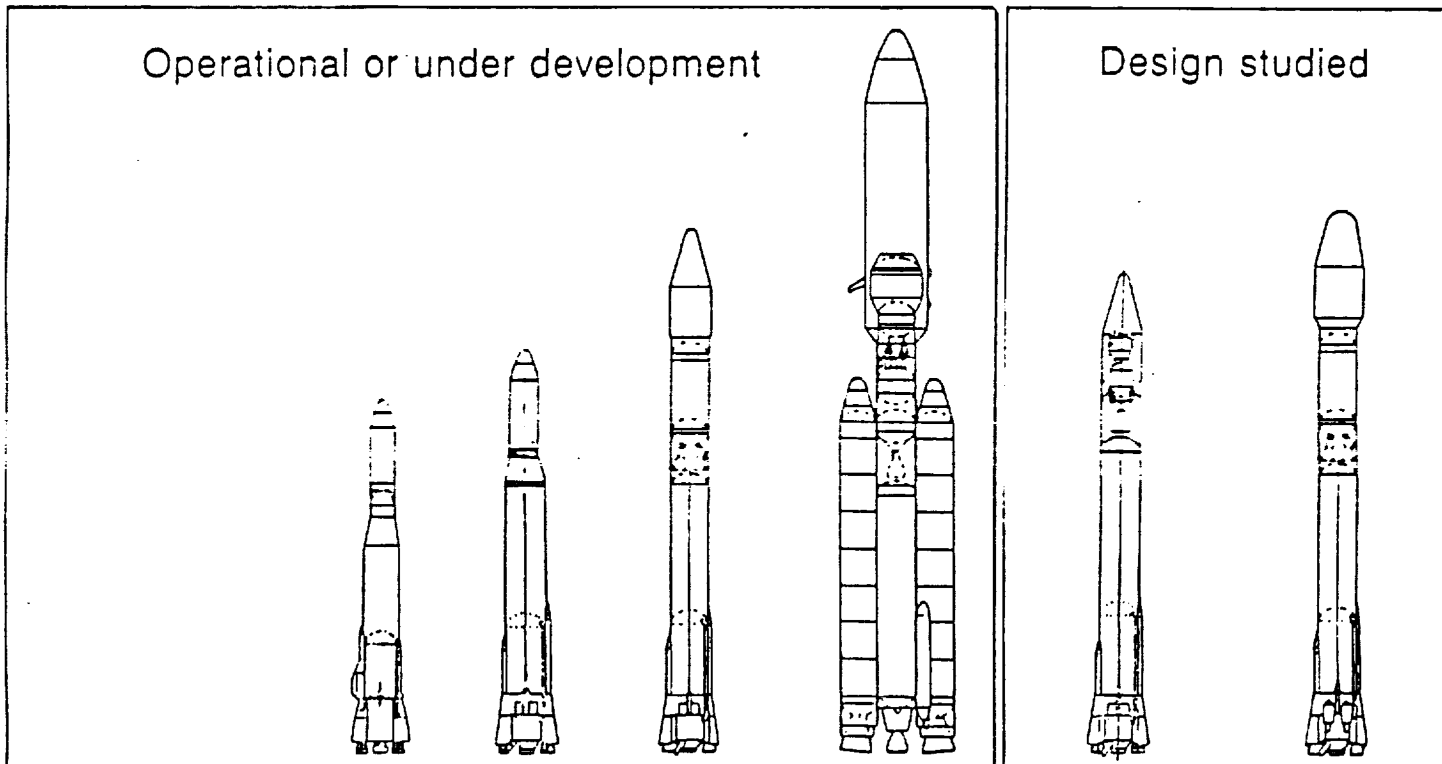
- Engines: strap-on boosters are graphite epoxy motors.

Enhanced Delta 2

- Engines: strap-on boosters are stretched graphite epoxy motors.
- This version of the Delta 7920 is being studied by the Air Force.

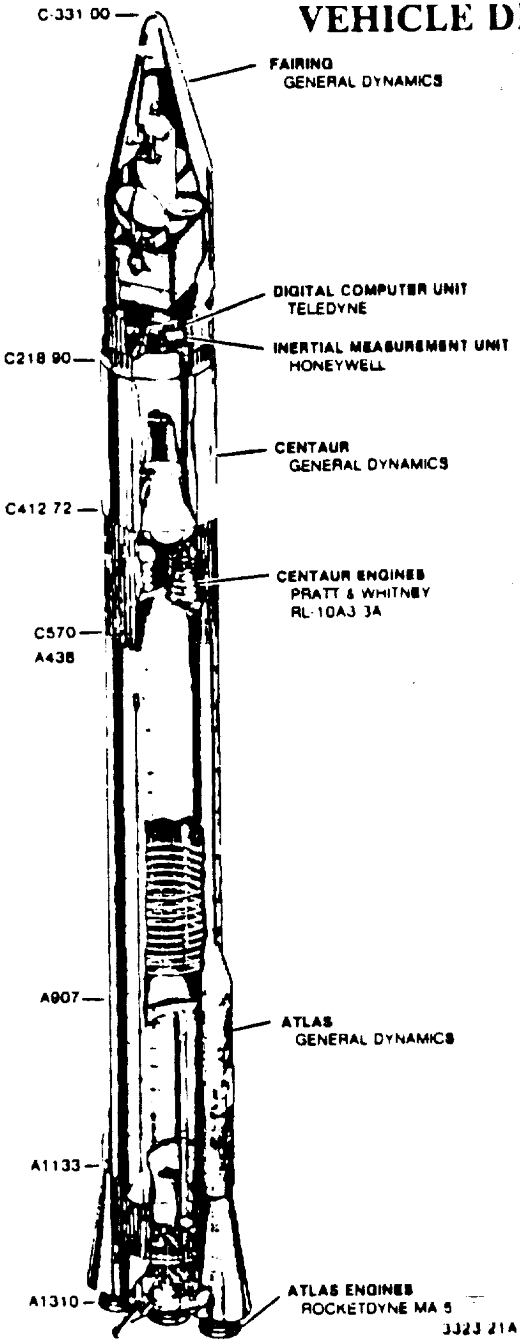
3.8 Proton Launch Vehicles

The Proton launch vehicles are four stage, liquid fueled rockets. The Proton is the primary heavy lift vehicle for the Soviet Union's space program. The vehicles have been launched 124 times since



Launch vehicle	Atlas E	Atlas H	Atlas G/Centaur	Titan $34D_7$/ Centaur	Atlas K	Super Atlas G/ Centaur
Performance (lb)						
• LEO	3,000	4,400	13,500	40,000	9,500	14,500
• GTO	N/A	N/A	5,200	20,000	3,500	6,000
Status	Operational	Operational	Operational	In development	Study completed	Study completed

Figure B–6: General Dynamics' Altas Vehicle and Centaur Booster Family



VEHICLE DESCRIPTION

Atlas G/Centaur D-1A is an improved version of the current Atlas SLV-3D/Centaur D-1A configuration.

Centaur D-1A, used in conjunction with Atlas G (Figure 2-1), incorporates the following improvements:

- Elimination of hydrogen peroxide boost pumps in the propellant supply system
- Replacement of hydrogen peroxide reaction control system with an equivalent hydrazine system
- Incorporation of a silver throat cast insert in the Pratt & Whitney engines (new designation: RL-10A-3-3A).

Atlas G is 81 inches longer than its predecessor, the SLV-3D booster. It also incorporates a booster thrust increase of 7,500 pounds leading to a vehicle liftoff thrust of 438,000 pounds. The vehicle will become operational on the AC-62 INTELSAT VA flight in December 1983.

CENTAUR SYSTEM SUMMARY

Length:	30 ft (9.14 m) without fairing
Diameter:	10 ft (3.05 m)
Guidance:	Inertial
Propulsion:	P&W RL 10A-3-3A
Rated Thrust:	33,000 lb (147 kN)
Rated I_{sp} (vac.):	446.4 sec
Propellants:	LO_2/LH_2; 30,750 lb (13,952 kg)
Centaur Jettison:	4,200 lb (1,905 kg)

Figure B-7: General Dynamics' Altas G/Centaur D-1A

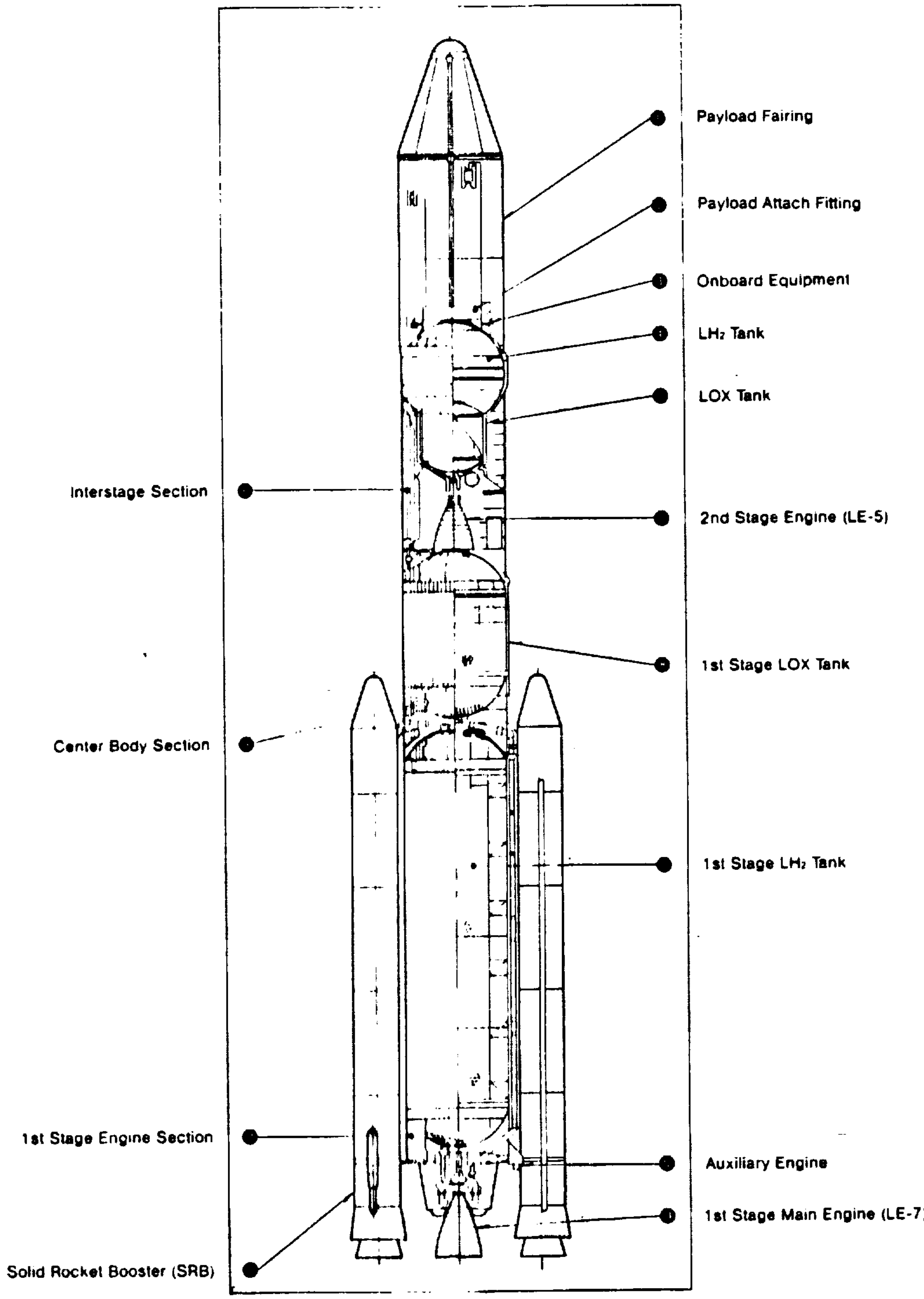
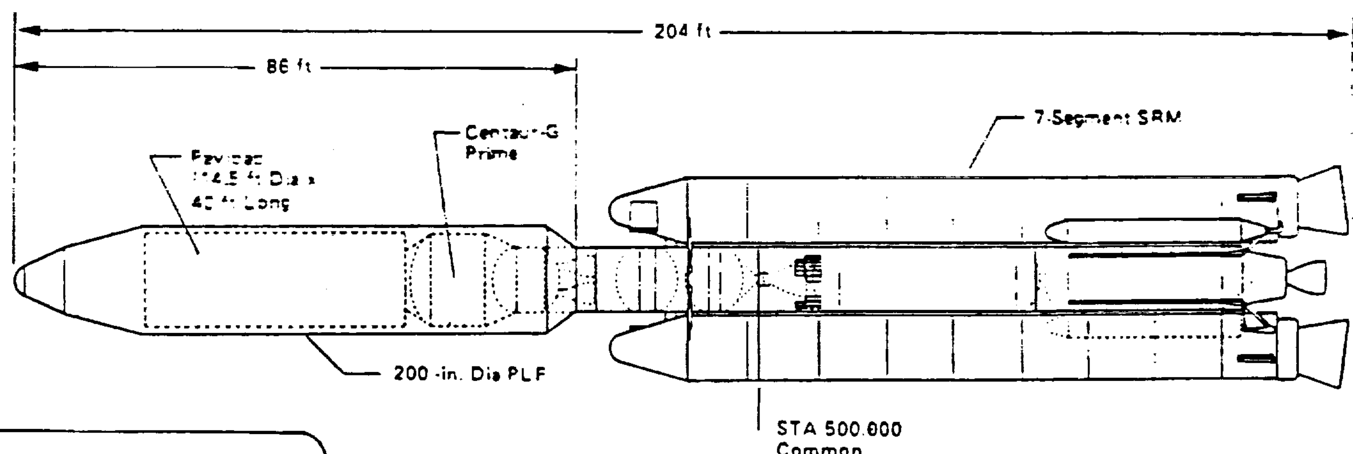


Figure B–8: Japan's H-II Launch Vehicle

	Solid Rocket Motors (Two)	Stage One	Stage Two	Centaur Upper Stage
Length	112.9 ft	86.5 ft	32.6 ft	29.3 ft
Diameter	10.0 ft	10.0 ft	10.0 ft	14.2 ft
Thrust	1.6 Million lb per Motor	546,000 lb	104,000 lb	33,000 lb
Propellants	Solid	Storable Liquid	Storable Liquid	Cryogenic

Guidance: Inertial with Digital Computer
Payload Fairing: 200 in Diameter, 86 ft Length, Tri-Sector Design, Isogrid Construction



Martin Marietta
Denver Aerospace
P.O. Box 179
MN-1200
Denver, Colorado 80201

Figure B–9: Martin Marietta's Titan 34D7 Launch Vehicle

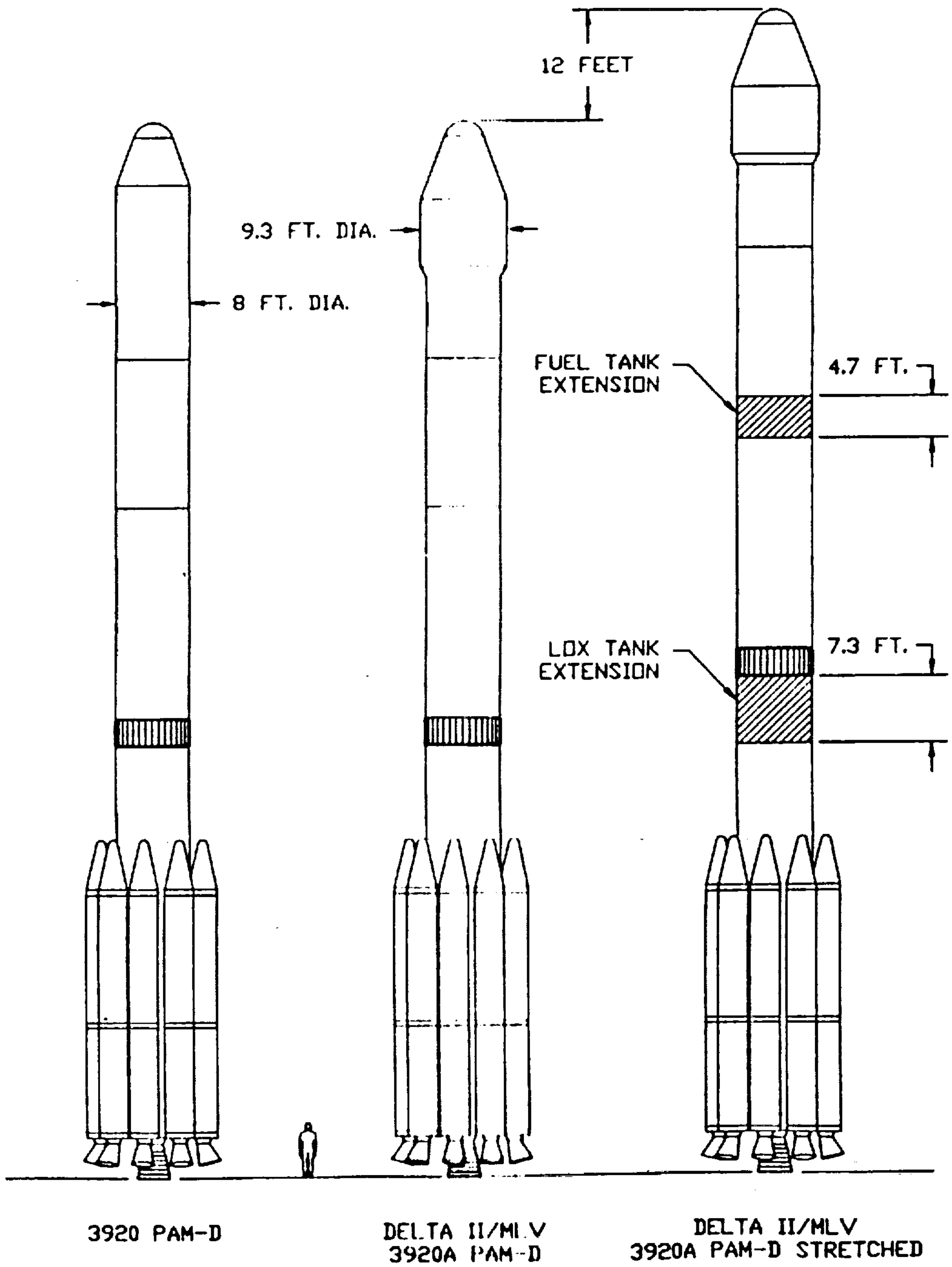


Figure B-10: McDonnell Douglas Aeronautics' Delta 2 Medium Launch Vehicle

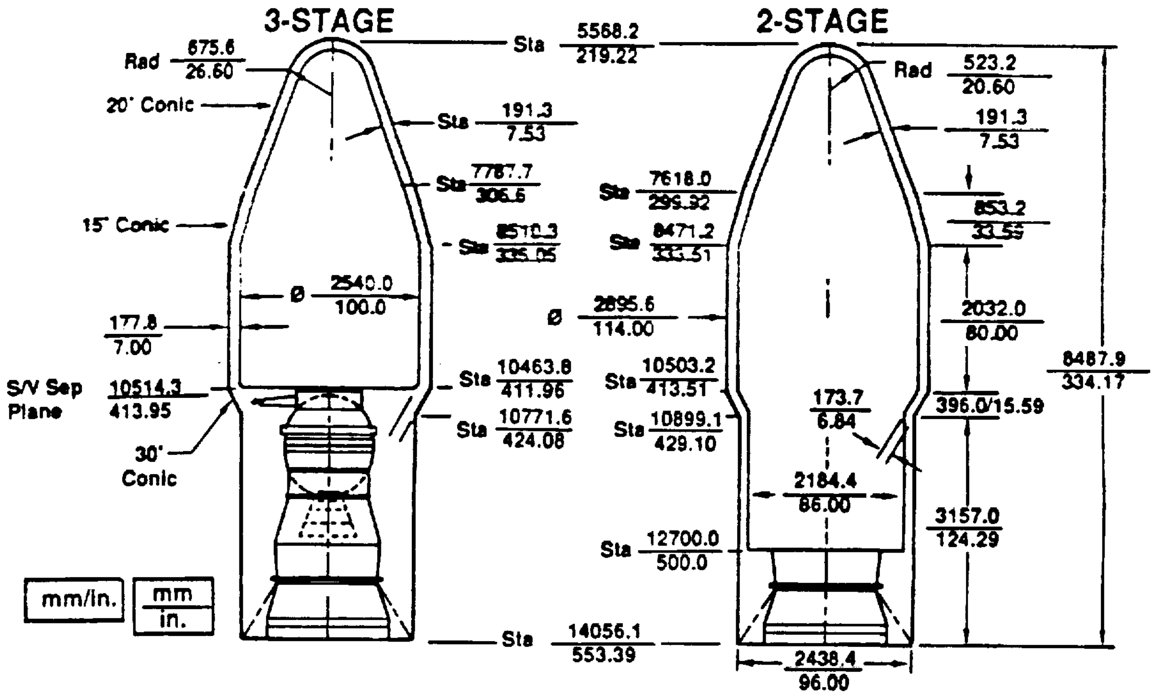


Figure B–11: Delta 2 Fairing Dimensions (9.5 ft diameter)

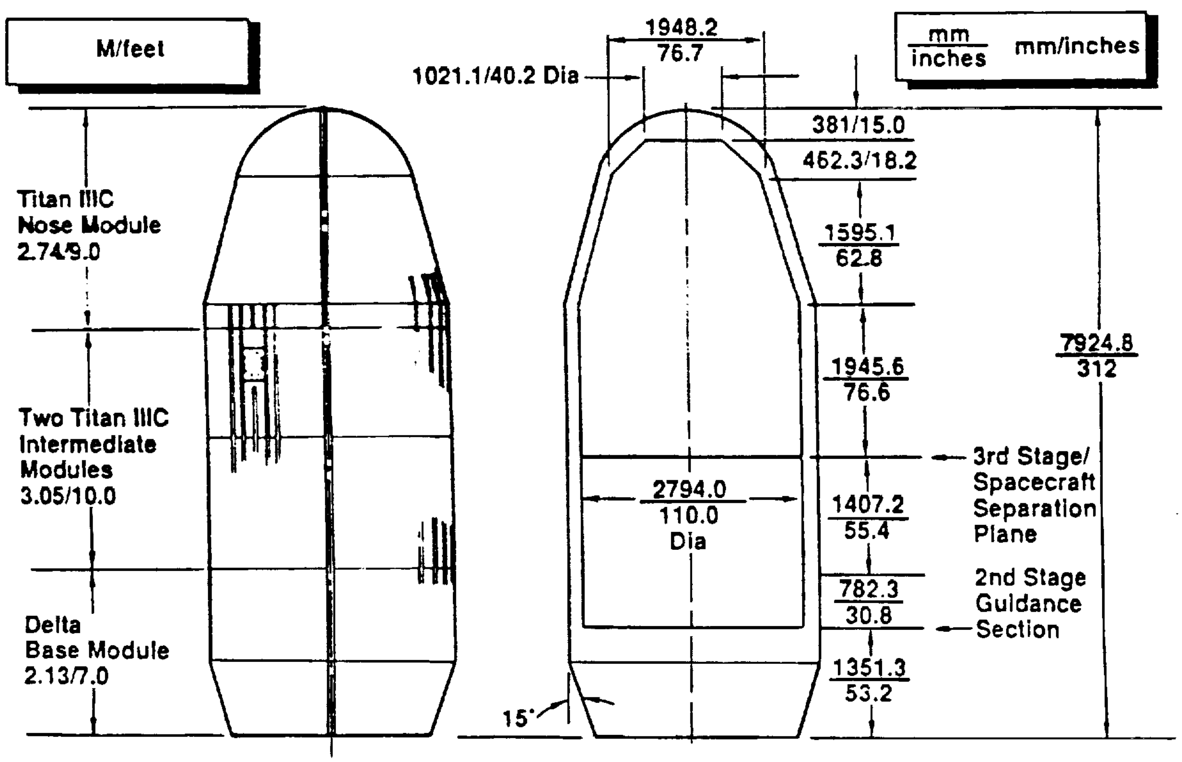


Figure B–12: Delta 2 Fairing Dimensions (10 ft diameter)

1970 with a 91% reliability rate. Figure B-13 shows the Proton D-1 SL-13 which has the following general characteristics:

- Engine:
  - First stage: six rotatable single-chamber liquid propellant engines.
  - Second stage: four rotatable single-chamber liquid propellant engines.
  - Third stage: one fixed single-chamber liquid propellant engine and one control liquid propellant engine with four rotatable nozzles.

Other members of the Proton family include the D-1/D SL-9 and the D-1-E SL-12.

3.9 Space Services' Conestoga

The core for all Conestoga launch vehicles consists of four stage, solid propellant motors, and measures 21 m in height. In September, 1984, the Conestoga I and a mock payload were launched on a suborbital flight. The rocket is designed for smaller payloads. Figure B-14 shows the Conestoga II.

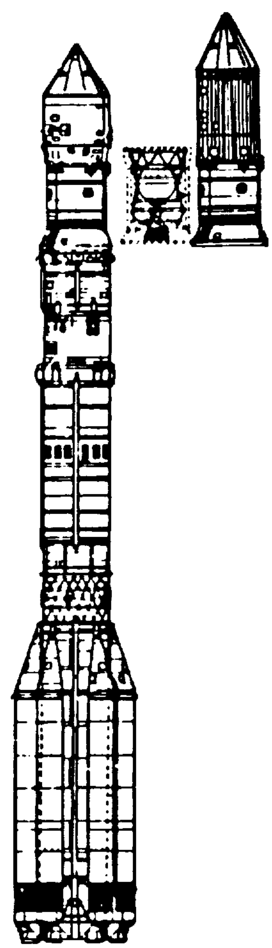
Conestoga II

- Stage 1: two Castor IV XL motors.
- Stage 2: one Castor IV XL motor.
- Stage 3: one Star 48 motor.
- Stage 4: one Star 30 motor.

Conestoga IV

- Stage 1: four Castor IV XL motors.
- Stage 2: two Castor IV XL motors.
- Stage 3: one Castor IV XL motor.
- Stage 4: one Pershing 1 motor.
- Stages 5 and 6: (a) one Star 48; or (b) one Star 37XF, or (c) one Star 37XF and one Star 27.

- Direct geosynchronous orbit performance capability:
    2000 Kg with D 4th stage accelleration unit
- Maximum payload envelope shape varies:
    3.3 M diameter (old shroud)
    4.2 M length
    3.0 M diameter (new shroud)
    5.2 M length
- Arian IV compatible shroud under development & test
- Low earth orbit performance capability:
    20,000 Kg (44,700 lbs)
- Direct insertion or 4,710 lbs into geostationary orbit. Higher mass can be placed in geo transfer orbit.
- Customer payload shroud revisions or other nations shroud accommodations available upon request
- Glavkosmos Launch Vehicle for spacecraft launch from Baykonure Cosmodrome



D-1 SL-13

Figure B–13: Proton D-1 SL-13 Launch Vehicle

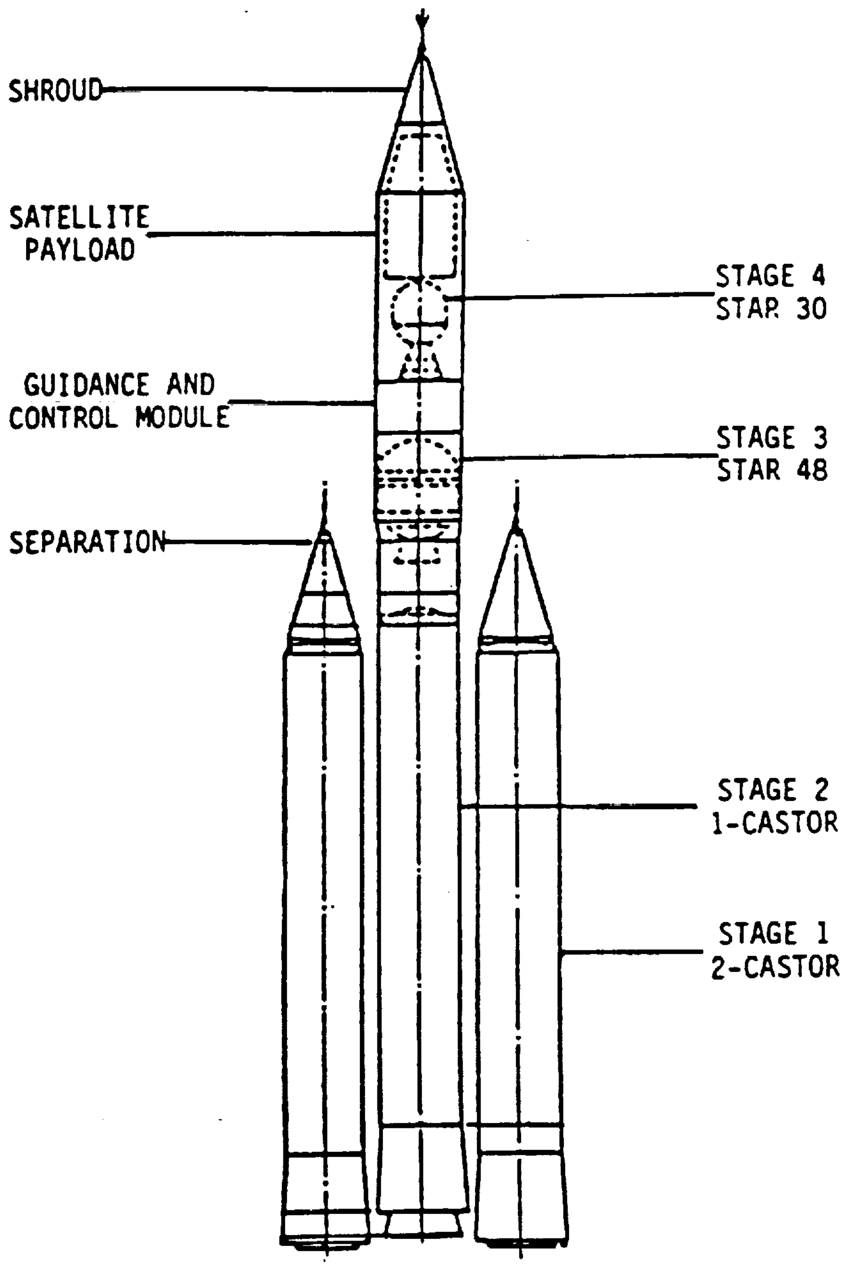


Figure B–14: Space Services Inc. – Conestoga 2

Appendix C
DOMSAT III FINANCIAL MODEL

1 Introduction

The discussion of this appendix is divided into five parts:

1. Introduction
2. Overview of the Model
3. Transportation Scenarios
4. Input Data Definitions
5. Example of Model

2 Overview of the Model

2.1 Background

DOMSAT III is a communications satellite financial planning model that is based on the DOMSAT II Model developed by *Princeton Synergetics Inc.* The purpose of the Model is to provide a means for evaluating the impacts of a broad range of programs and policies on the financial performance of communications satellite business ventures. The DOMSAT II model has been modified so as to include space operations that utilize ground-based and space-based facilities. The result is the DOMSAT III Model, hereafter referred to as "the Model".

2.2 Purpose of Model

The Model can be used to establish the impacts on the financial performance of communications satellite business ventures of the following items:

- Spacecraft technology programs such as on-orbit propulsion and space power.
- Use of alternative space transportation systems (i.e. Shuttle, Ariane, Proton)
- Achieving improved final payload placement accuracy (in GEO).
- Different insurance rates as compared with the self insurance option explicitly taking into account the level of risk (insurance may be considered separately for each operation including launch to LEO, checkout in LEO, transfer from LEO to GEO and initial P/L startup.
- Transportation system technology programs (for example, low thrust from LEO to GEO; improved upper stage reliability).
- Space transportation system pricing policies.
- Pricing policies for transponders and related services
- Spacecraft configuration alternatives including transponder arrangements and sparing concepts.
- Regulatory programs.

In addition, the Model is specifically configured so that it can be used to establish the impacts on the financial performance of communications satellite business ventures of the following items:

- Alternative placement, replacement, service, repair policies utilizing ground-based facilities.
- Alternative placement, replacement, service, repair policies utilizing space-based facilities.

All of the above may be accomplished directly by altering the input data associated with typical business scenarios so as to reflect the technology attributes or policy issues of concern. These may vary over time. The above program and policy impacts are established in terms of the financial impacts on specific business scenarios (at the macro level) and include explicit and quantitative measures of risk.

The Model provides the means for evaluating the financial impacts of spacecraft technology programs, space transportation programs, utilization of space-based facilities, and alternative placement, replacement, service-repair policies on communications satellite business ventures. It specifically allows for the consideration of hybrid (i.e. C and Ku band) satellite configurations.

The anticipated results of technology programs or policy decisions are converted into cost, performance and reliability attributes which form inputs to the Model. These estimates are combined with a business scenario (see Paragraph C-2.3) to establish annual profit (loss), annual cash flow, cumulative cash flow, ROA, payback period, and return on investment. The financial performance measures are all described by probability distributions (i.e. risk profiles) since cost uncertainties (i.e. uncertainty profiles) and subsystem reliability are considered.

The impact of technology programs and policy decisions can be assessed in terms of the changes in financial performance measures that result from differences in performance, cost and service attributes resulting from the programs and policy decisions. Two analyses are necessary. One analysis is based upon a satellite configuration and business scenario in the absence of the technology program or policy decision (the baseline case). The second analysis is based upon a satellite configuration and business scenario incorporating the assured results of the technology program or policy decision. The difference in the financial results is assumed to be directly attributable to the technology program or policy decision.

2.3 The Business Scenario

The Model allows a business scenario to be specified in terms of the following items:

- Number of years in the business plan.
- Maximum number of operational satellites.
- Desired launch schedule.
- Identification of initial placement or maintenance transportation scenarios as a function of time selected from the following scenarios:

    1. Direct placement using ground-based assets
    2. Placement and return using ground-based assets
    3. On-orbit repair using ground-based assets
    4. Replace/return/repair using ground-based assets
    5. Direct placement using space-based assets
    6. Placement and return using space-based assets
    7. On-orbit repair using space-based assets
    8. Replace/return/repair using space-based assets
    9. Return/replace/repair on and from space-based assets.

    Subsections C-3 and C-4.3, and Figures C-1 through C-9 contain more complete descriptions of the scenarios.

- Probability of success of each of the major steps in the selected launch and maintenance scenarios.
- Transportation cost associated with each major operation in the selected launch and maintenance scenarios and cost spreading.
- Identification of specific operations for which insurance will be taken.

- Insurance cost (expressed as a multiplier of expected loss) for each operation and cost spreading.
- Possible launch delays (in terms of failure type).
- Number of narrow band transponder groups per satellite.
- Number of wide band transponder groups per satellite.
- Number of transponders per narrow band group.
- Number of transponders per wide band group.
- Number of spare transponders per narrow band group.
- Number of spare transponders per wide band group.
- Transponder reliability characteristics (mean time to failure, expected wearout life, variability of wearout life).
- Spacecraft support subsystem (up to 5) reliability characteristics.
- Types of communication service provided (protected, protected-preemptible, unprotected, and preemptible).
- Rates per narrow and wide band transponders for each type of communications service.
- Annual demand for narrow and wide band transponders in terms of type of service.
- Relaunch threshold in terms of number of operational transponders.
- Annual cost of spacecraft operations.
- Annual G&A expense (fixed and variable).
- Annual R&D expense (fixed and variable).
- Other annual expenses (fixed and variable).
- Spacecraft unit recurring cost and cost spreading.
- Spacecraft nonrecurring cost and cost spreading.
- Spacecraft unit recurring cost learning rate.
- Depreciation lives.
- Interest rate.
- Tax related data.
- Discount rates.
- Balance sheet related data.

Many of the above variables are considered as uncertainty variables requiring the specification of the range of uncertainty and the form of uncertainty.

2.4 General Description

2.4.1 Uncertainty and Reliability

The Model allows uncertainty and reliability (initial, random and wearout failures) to be considered explicitly and quantitatively. This is absolutely necessary when considering programs and policies which are specifically aimed at reducing uncertainty and altering reliability both of which effect perceived risk and hence effect investment decisions. To establish the quantitative measures of risk, the model utilizes Monte Carlo techniques wherein the complete business scenario is simulated a large number of times (typically 1,000 or more), each time randomly sampling from the uncertainty profiles and the reliability characteristics which are specified. The results of all the business analyses are saved and histograms developed of the financial performance measures.

2.4.2 Performance Measures

The Model develops many financial performance measures (i.e. the economic performance measures) including annual after tax profit, annual cash flow, cumulative cash flow, return on sales , return on assets, payback period, and net present value. Expected values and standard deviations are establiblished for all of these. The net present value is established at a number of discount rates so that the internal rate of return can easily be established.

2.4.3 Architecture

The Model consists basically of two parts. The first, utilizing the desired schedule of events, demand for communications services, the satellite configuration, specified launch scenario and reliability characteristics, establishes the specific timing and number of events and their costs. The availability of transponders (taking into account failures, sparing concepts and services offered) is matched against demand in order to establish the schedule for replacement or maintenance flights and the timing of additional capital expenditures for replacement satellites and launches. The timing and cost information is then passed to the second part of the Model which performs the financial computations and establishes values of the economic performance measures.

The Model is implemented such that certainty conditions can be easily analyzed as well as the uncertainty situations. For example, the number of desired runs is an input parameter and can be set to one when all ranges of uncertainty are set to zero (i.e. minimum and maximum values are set equal).

The data is entered into the Model via Lotus 1-2-3, and the Model is written in Fortran. The system has been designed for operation on the IBM PC with all Model programs residing on a single diskette.

3 Transportation Scenarios

The following nine transportation scenarios were developed by *Princeton Synergetics* for use with the Model. The first four pertain to operations utilizing ground-based assets and the remaining five scenarios use space-based assets (Space Station).

1. Launch satellite to orbit from earth.

2. Replacement and return of failed satellite to earth for repair:
   a. Launch Satellite 2 from earth.
   b. Rendezvous with, retrieve, and return Satellite 1 to earth.

3. On-orbit repair from earth:
   a. Rendezvous with failed satellite in orbit.
   b. Repair satellite in orbit.

4. Retrieve satellite from orbit to earth for repair or salvage.
   a. Rendezvous with of failed satellite in orbit.
   b. Retrieve and return satellite to earth.

5. Launch satellite to orbit from earth via Space Station:
   a. Transport satellite to Space Station from earth.
   b. OTV launches satellite; OTV returns to Space Station.

6. Launch Satellite 2 and retrieve Satellite 1 to earth via Space Station:
   a. Transport Satellite 2 to Space Station; launch with OTV.
   b. Rendezvous with and retrieve failed Satellite 1 to Space Station.
   c. Transport failed Satellite 1 to earth.

7. On-orbit repair from Space Station:
   a. Launch repair kit from earth to Space Station.
   b. OTV repair mission to rendezvous with failed satellite and repair on-orbit.

8. Retrieve failed satellite from orbit for earth repair or salvage via Space Station:
   a. OTV retrieval mission to orbit; rendezvous failed satellite.

b. OTV return to Space Station with failed satellite.

c. Failed satellite returned to earth for repair or salvage.

9. Launch Satellite 2, retrieve Satellite 1, repair at Space Station:

   a. Transport Satellite 2 to Space Station from ground; OTV launches Satellite 2.

   b. OTV retrieves Satellite 1 from orbit and returns it to the Space Station.

   c. Repair Satellite 1 at Space Station using parts as required from earth.

These scenarios are illustrated in Figures C-1 through C-9, and are discussed in greater detail in Paragraph C-4.3. The orbital transfer vehicle (OTV) is used for transportation from low earth orbit (LEO) to geosynchronous earth orbit (GEO). (Although the schematic of Figure C-1 shows a Shuttle and OTV, expendable launch vehicles could be used for direct placement to GEO.)

The OTV upper stage can be used to place satellites in orbit. However, to rendezvous with an orbiting satellite, an orbital manuevering vehicle (OMV) must be carried up to GEO by the OTV. The OMV is required for the following reasons:

- The OMV can do fine maneuvers and match spin rate with the orbiting satellite.
- The OMV has a non-reactive gas (nitrogen) propulsion system for use in the vicinity of a satellite. (It doesn't produce by-products that could damage the satellite.)

For servicing or repair in orbit, a remote servicing unit must also be carried up to GEO. Thus Scenarios 3 and 7 use the OMV plus servicer with repair kit.

4 Input Data Definitions

The Model input data definitions are divided into 49 parts. These parts are denoted in square brackets (for example [1]) on the input data spreadsheets. For purpose of description, the 49 input data parts are divided into the following 17 categories and described in the 17 paragraphs of this subsection:

1. Global Data (System) [1]
2. Global Data (Financial) [2]
3. Transportation Scenarios [3]
4. Launch Scenario Data [4–12]
5. Payload Cost Data [13]
6. Insurance Data [14]
7. Transponder Data [15]
8. Spacecraft Subsystem Data [16]
9. Transponder Demand Data [17–36]
10. Transponder Price Data [37–40]
11. Price Elasticity Data [41]
12. Correlation Data [42]
13. Spacecraft Control Operations Cost [43]
14. Engineering, R&D, and G&A [44–46]
15. Capital Expenditure Data [47]
16. Uncertainty Profile Data [48]
17. Repair Replacement Decisions [49]

4.1 Global Data – System [1]

The Global System Data describes the broad parameters of the business system that is described by the data in this section. There are five categories of global system data:

1. **NO YRS ANALYZED** is the number of years to be considered in the business plan (must be equal to or less than 15).
2. **MAX NO OPER SATS** is the maximum number of operational satellites to be considered in the business plan (must be equal to or less than 5).

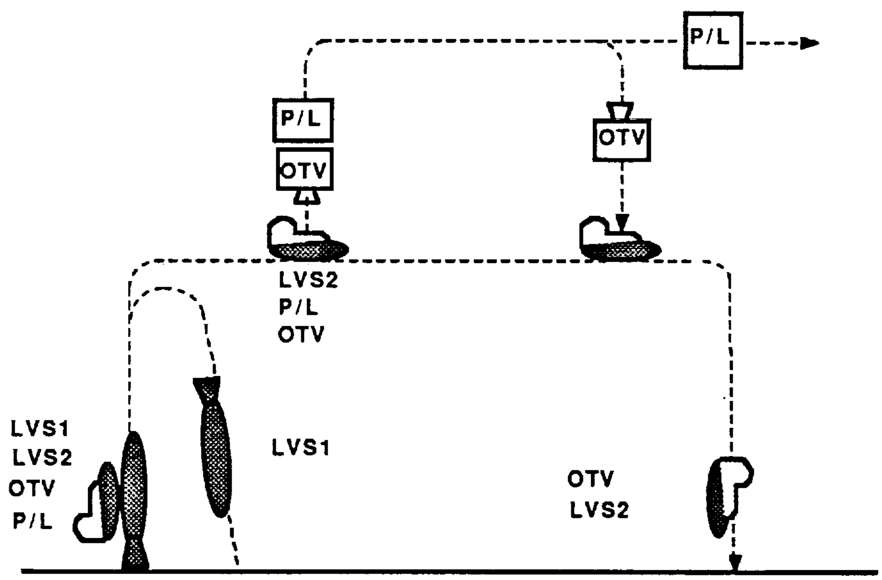


Figure C–1: Scenario 1: Direct Placement Using Ground-Based Assets

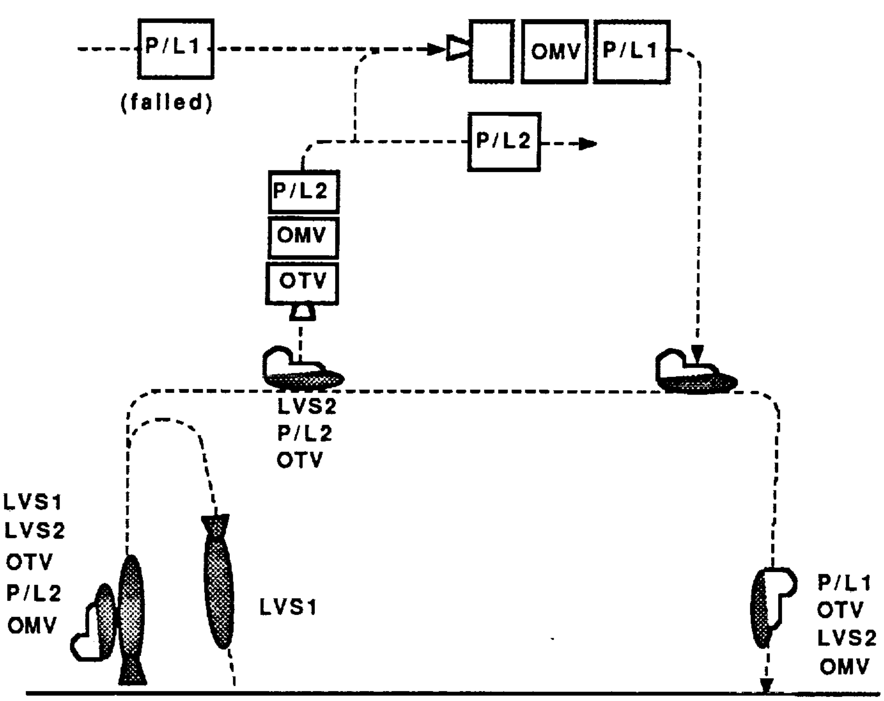


Figure C–2: Scenario 2: Replacement and Return Using Ground-Based Assets

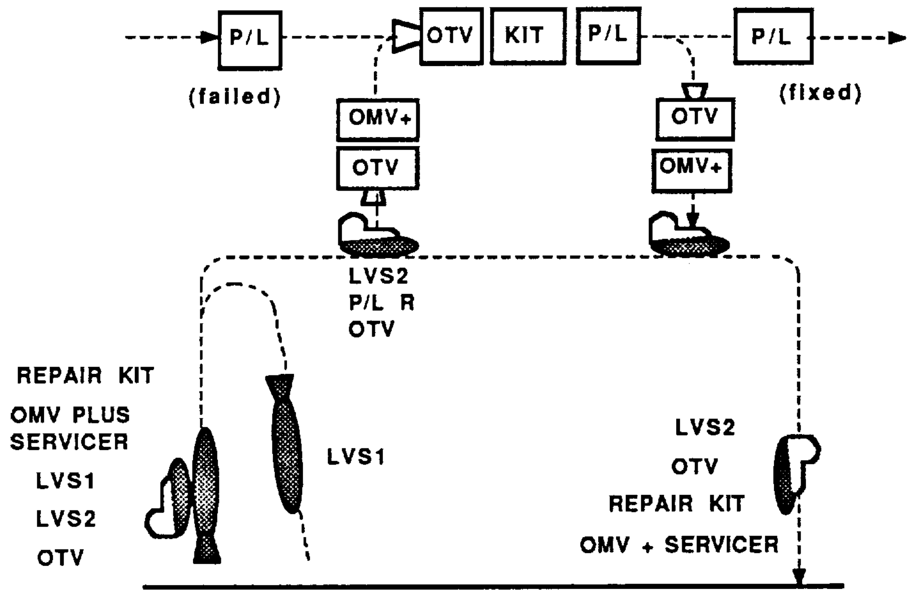


Figure C–3: Scenario 3: On-Orbit Repair Using Ground-Based Assets

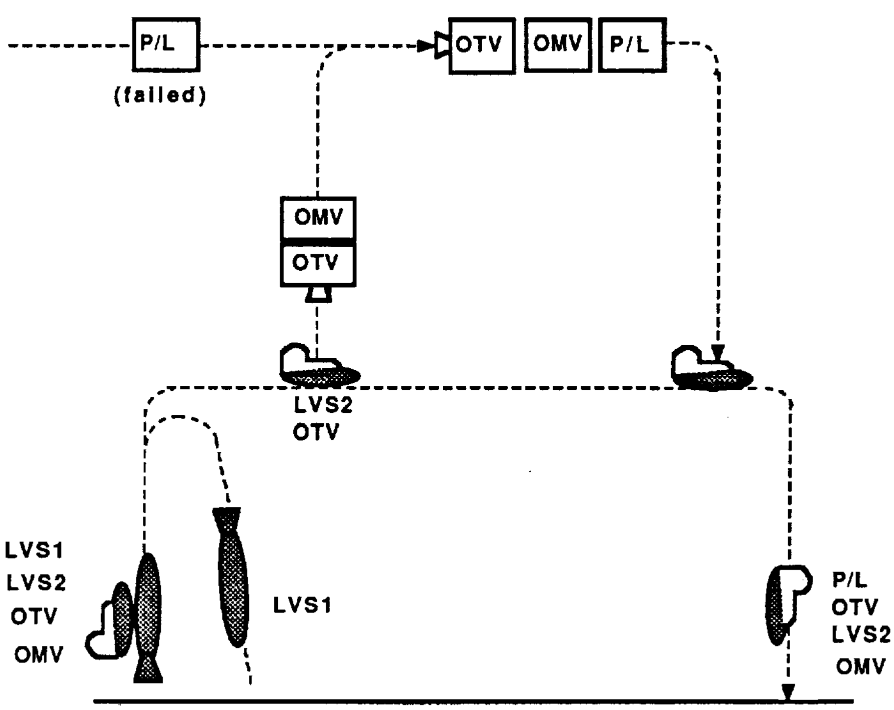


Figure C–4: Scenario 4: Retrieve to Earth for Repair Using Ground-Based Assets

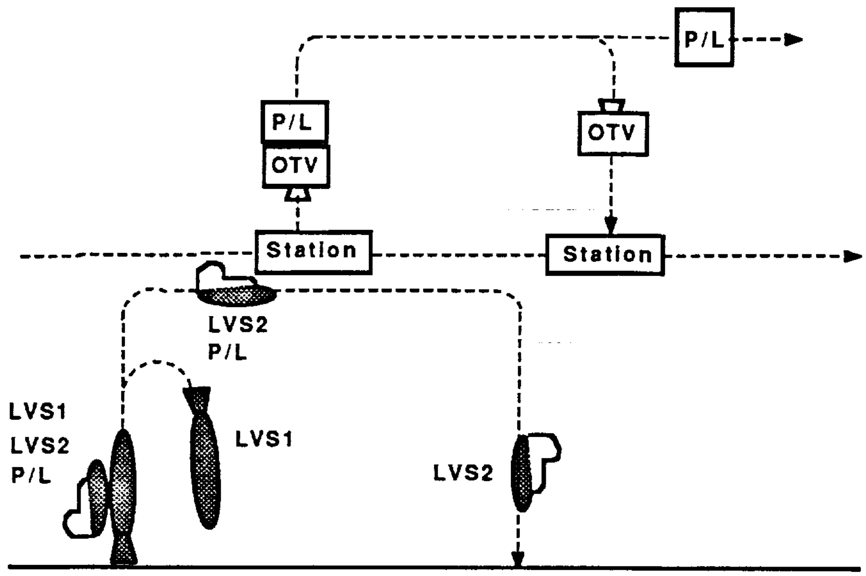


Figure C–5: Scenario 5: Direct Placement Using Space-Based Assets

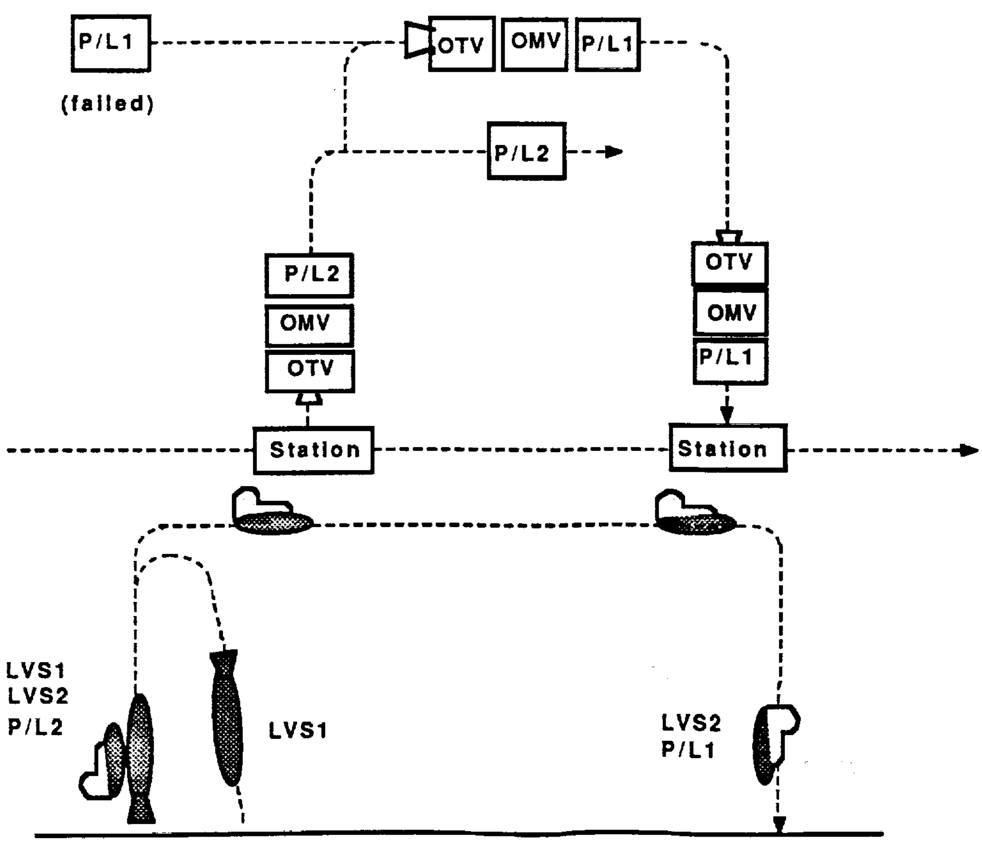


Figure C–6: Scenario 6: Replace, Retrieve to Earth for Repair Using Space-Based Assets

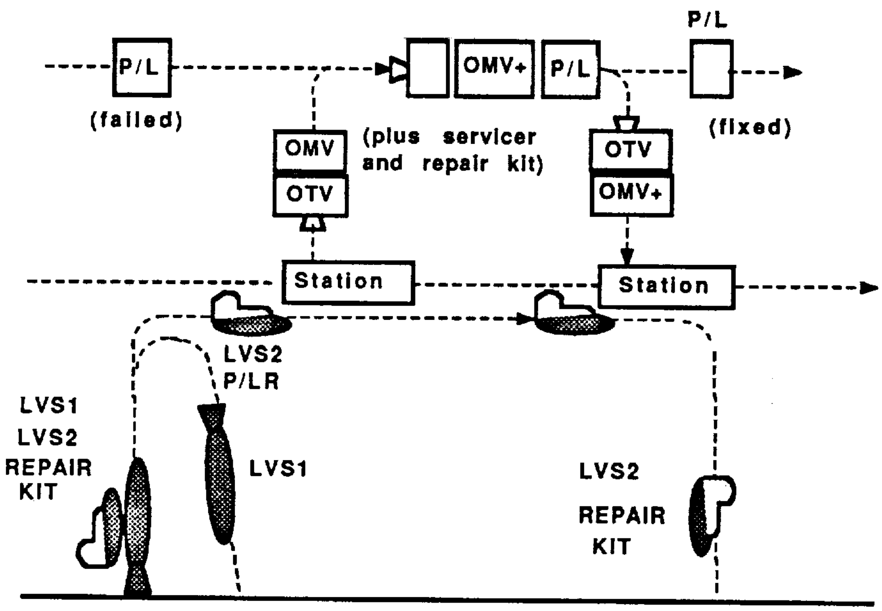


Figure C–7: Scenario 7: On-Orbit Repair Using Space-Based Assets

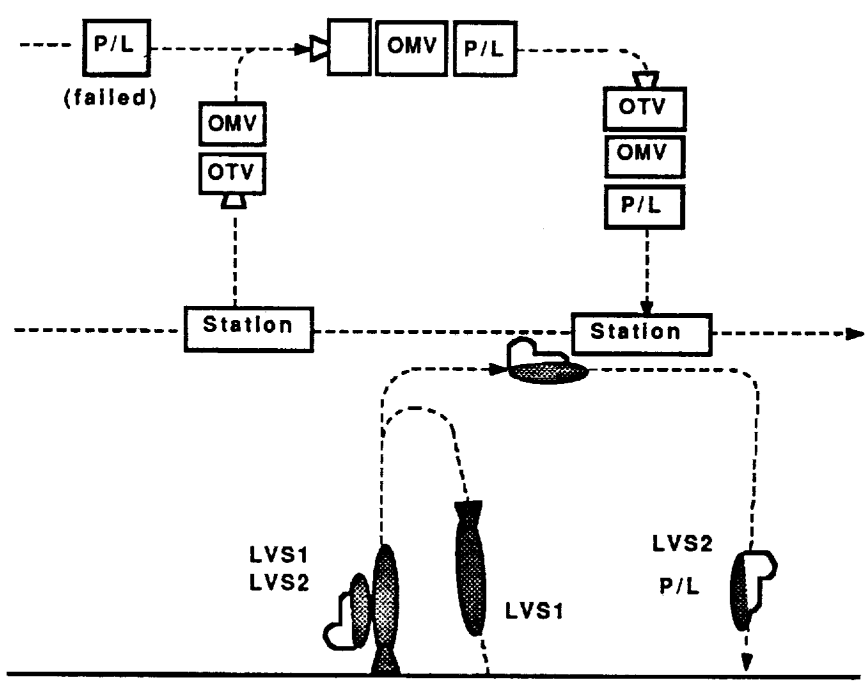


Figure C–8: Scenario 8: Return to Earth for Repair Using Space-Based Assets

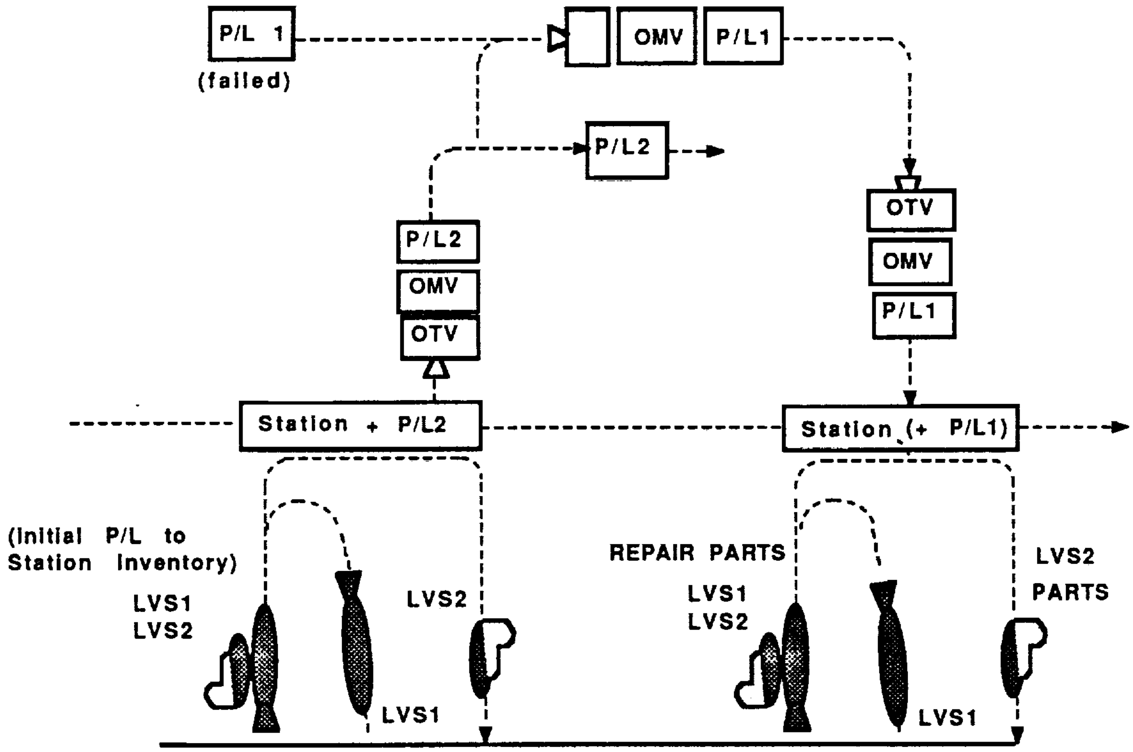


Figure C–9: Scenario 9: Replace, Return to Station for Repair Using Space-Based Assets

3. **MAX NO LNCH SCEN'S** is the maximum number of launch scenarios active in the Model (currently equal to 9).

4. **LAUNCH DATES (YRS)** is the desired initial launch date for each of the operational satellites (i.e. 5.5 indicates that the initial launch attempt for the second operational satellite will occur half-way through year 5). When an operational satellite fails it will be replaced. For example, with the indicated data the objective is to maintain 3 operational satellites after year 7.5.

5. **NO SIMUL RUNS** is the number of simulation runs to be performed in the Monte Carlo analysis.

Table C-1 shows the form of the global data (system) input menu with some data entered.

No. Yrs. Analyzed	15
Max. # Oper. Sats	3
Max. # Lnch Scen's	9
Desired Lnch Date (yr)	
Satellite No. 1	4.0
Satellite No. 2	5.0
Satellite No. 3	6.0
Satellite No. 4	.0
Satellite No. 5	.0
No. Simul. Runs	1000

Table C–1: Global Data (System) Menu [1]

4.2 Global Data – Financial [2]

The Global Financial Data establishes the underlying financial parameters to be used in the planning and evaluation of the business venture. There are ten categories of global financial data:

1. **DEBT SVC INT RT (%)** is the debt service interest rate expressed as a percentage.

2. **EFFECT TAX RATE (%)** is the effective tax rate expressed as a percentage. It is assumed that the communications satellite business venture is part of a large corporation where profits and losses are consolidated.

3. **INVEST TAX CRDT (%)** is the investment tax credit expressed as a percentage.

4. **TAX CREDIT ON.** The input data specifies whether or not investment tax credits are taken on launch cost, insurance cost, spacecraft recurring cost, and other capital expenditures. A "1" indicates that tax credits are taken and a "0" indicates that tax credits are not taken.

5. **PAYABLES (% EXP).** Average number of weeks of outstanding payables expressed as a percentage (for example, 6 weeks of payables is equal to 11.5% - 6/52 of a year).

6. **RCVS (% REV)** is the average number of weeks of outstanding receivables expressed as a percentage (for example, 6 weeks of receivables is equal to 11.5%).

7. **CASH (% REV)** is the amount of cash, expressed as a percentage of annual revenue, required to meet current expenses.

8. **S/C LEARN RATE (%).** Spacecraft learning rate expressed as a percentage. The S/C unit recurring cost is reduced by a percentage equal to 100 minus the learning rate every time the number of years (from the first launch) doubles.

9. **DEPREC LIFE (YRS).** The depreciation life (years) for launch, insurance and spacecraft, and other capital expenditures. Straight line depreciation is utilized.

10. **DISCOUNT RATE (%)** is the discount rates (%) utilized in the computation of net present value of cash flow. The present value is established at five discount rates.

Debt SVC Int Rt %	11.0
Effect Tax Rate %	38.6
Invest Tax Crdt %	.0
Tax Credit On	
Launch Cost	1
Insurance Cost	1
S/C Recur. Cost	1
Other Cap. Exp.	1
Payables (% Exp.)	8.3
RCVS (% Rev.)	16.7
Cash (% Exp.)	1.5
S/C Learn Rate %	90.0
Deprec. Life (yrs)	
Launch Ins, S/C	5.0
Other Cap. Exp.	10.0

Discount Rate (%)	10	15	20	25	40

Table C–2: Global Data (Financial) Menus [2]

Table C-2 shows the form of the global data (financial) input menu with some data entered.

4.3 Transportation Scenarios [3]

Nine transportation scenarios are contained within the Model; four pertain to operations utilizing ground-based assets and five pertain to operations utilizing space-based assets. These scenarios are illustrated in Figures C-1 through C-9 and illustrate reusable systems. It should be noted that an expendable system (for modeling purposes) is a reusable system with the probability of recovery equal to zero.

For each year of the analysis two transportation scenarios must be identified; one for initial payload (P/L) placement operations and the other for P/L maintenance/repair operations. The same scenario may be identified for both initial placement and maintenance-repair operations and the scenarios to be considered may vary from year to year.

It is assumed that a transportation system consists of a generic launch vehicle (LV) that contains two stages (LVS1 and LVS2) and a generic orbital transfer vehicle (OTV). (Each of these stages may actually contain other stages but can be considered from a reliability, cost and recovery point of view as being lumped into a single stage.)

A brief description of each of the nine transportation scenarios is given. This is followed by Paragraph C-4.3.10 which discusses the specification of the scenarios.

4.3.1 Transportation Scenario 1

Scenario 1 consists of a reusable LV (note that LVS1 may be reusable or expendable) or LV and OTV or expendable LV and OTV for initial P/L placement and/or replacing failed P/Ls. Scenario 1 may be used in conjunction with Scenario 4 for the placement portion of the replace-return-repair mission. If reusable launch vehicles are considered, OTV and P/L checkout failures in LEO may be corrected when and if returned to Earth.

4.3.2 Transportation Scenario 2

Scenario 2 consists of a reusable LV and OTV for placing a P/L into orbit and returning a failed P/L in the same OTV flight. If reusable launch vehicles are considered, OTV and P/L checkout failures in LEO may be corrected when and if returned to Earth.

4.3.3 Transportation Scenario 3

Scenario 3 consists of a reusable LV, LV and OTV, or expendable LV and OTV for performing on-orbit repair at the P/L location. It is assumed that the OTV plus OMV is required for docking with specifically configured P/Ls. If repair cannot be accomplished, a replacement is performed using an appropriate specified scenario. If reusable launch vehicles are considered, OTV checkout failures may be corrected when and if returned to Earth.

4.3.4 Transportation Scenario 4

Scenario 4 consists of a reusable LV and OTV for acquiring and returning a failed P/L. The OMV is transported by the OTV and is capable of docking with specifically configured P/Ls. Replacement is performed prior to returning the failed P/L by use of an appropriate specified scenario. If reusable launch vehicles are considered, OTV checkout failures may be corrected when and if returned to Earth.

4.3.5 Transportation Scenario 5

Scenario 5 consists of a reusable or expendable LV for transporting P/Ls to the Space Station. The OTV, based at the Space Station, is used to place the P/L into final orbit. The OTV may be reusable or expendable. It is assumed that P/L and OTV checkout failures can be corrected at the Space Station.

4.3.6 Transportation Scenario 6

Scenario 6 consists of a reusable LV and OTV for placing a P/L into orbit and returning a failed P/L in the same OTV flight. The reusable LV provides the new P/L to the Space Station and returns the failed P/L from the Space Station to Earth. It is assumed that P/L and OTV checkout failures can be corrected at the Space Station.

4.3.7 Transportation Scenario 7

Scenario 7 consists of a reusable LV, LV and OTV, or expendable LV and OTV for performing on-orbit P/L repair. The OTV and OMV are located at the Space Station. It is assumed that the OMV is capable of docking with specifically configured P/Ls. If repair cannot be accomplished, replacement will be accomplished either via Scenarios 1 or 5 (as specified). It is assumed that OTV checkout failures can be corrected at the Space Station. A repair-kit is delivered from the Earth to the Space Station and, upon mission completion, returned to Earth.

4.3.8 Transportation Scenario 8

Scenario 8 consists of a reusable OTV for acquiring and returning failed P/L to the Space Station. The P/L is then returned to Earth for repair using a reusable LV. It is assumed that the

OMV is capable of docking with specifically configured P/Ls. Replacement is performed (prior to returning failed P/L) using an appropriate specified scenario. It is assumed that OTV checkout failures can be corrected at the Space Station.

4.3.9 Transportation Scenario 9

Scenario 9 consists of a reusable LV and OTV transportation system for placing a P/L into orbit and returning a failed P/L in the same OTV flight. A P/L is stored on the Space Station and repair is performed on the Space Station. An initial flight is required to place a P/L into inventory on the Space Station.

4.3.10 Specification of Scenarios

The transportation scenarios to be used for placement and repair are specified as follows:

1. **INIT PLACEMENT.** The identity number (1 or 5) of the transportation scenarios (Figures C-1 and C-5) that are to be used for initial P/L placement flights. (Specify for each year of the time horizon.)

2. **MAINT & REPAIR.** The identity number (1 through 9) of the transportation scenarios (Figures C-1 through C-9) that are to be used for repair flights. Repair encompasses replacement when on-orbit repair is not to be considered. (Specify for each year of the time horizon.)

3. **STORAGE COST.** The annual cost (M$/year) for storing a P/L on the Space Station. (Required only when the Maintenance and Repair Scenario ID = 9.)

Table C-3 shows the form of the input menus for the transportation scenarios and Space Station storage cost. (Note that these menus extend from 1 to 15 years, but only a few years are shown in this table.

Transportation Scenarios

	Year			
	1	2	...	15
Initial Placement	1	1		1
Maint. & Repair	1	1		1

Space Station Storage Cost

	Year			
	1	2	...	15
Storage Cost (M$/yr)	0.0	0.0		0.0

Table C–3: Transportation Menus [3]

4.4 Launch Scenario Data [4–12]

The launch scenario data is required for each of the scenarios used ([4] is Scenario 1, [5] is Scenario 2, ... , [12] is Scenario 9) and for each year out to the specified time horizon. The data consists of three parts:

- Launch reliability data
- Launch delay data
- Launch cost data

The transportation scenario data contains a statement of the estimated probability of success of each of the major steps in the launch and repair sequence. It also contains a statement of possible delays if certain types of failures occur as well as cost data.

Both the delay and cost data may be described as ranges of uncertainty (i.e. maximum and minimum values) and the form of the uncertainty (i.e. the ID of the uncertainty profile or probability density function associated with the range of uncertainty – the uncertainty profile data is described in Paragraph C-4.16). Note that setting the maximum and minimum values equal to each other results in a certainty case with the ID of the uncertainty profile being immaterial.

4.4.1 Launch Reliability Data

The launch reliability data consists of the following 11 items:

1. **LVS1 SUCCESS.** The probability of booster or first-stage (LVS1) success.

2. **LVS2 RECV: LVS1 FAIL.** The probability of launch vehicle stage two (LVS2) recovery given a LVS1 failure.

3. **LVS2 SUCC: LVS1 SUCC.** The probability of LVS2 success given a LVS1 success.

4. **LVS2 RECV:LVS2 ABOR.** The probability of LVS2 recovery given a LVS2 abort prior to reaching LEO.

5. **OTV CHECKOUT SUCC.** The probability of successful checkout of the OTV in LEO.

6. **LVS2 RECV: LVS2 SUCC.** The probability of LVS2 success given an otherwise successful flight.

7. **OTV TRANSFER SUCC.** The probability that the OTV will transfer successfully from LEO to GEO.

8. **P/L CHECKOUT IN LEO.** The probability that the P/L will checkout successfully in LEO (or on the Space Station).

9. **P/L OK IN GEO.** Probability of payload operating successfully when in final orbit.

10. **OTV REC: OTV SUCC.** Probability of OTV return and rendezvous with LVS2 or Space Station given an otherwise successful OTV flight.

11. **OTV RENDEZVOUS.** Probability that OTV will be able to rendezvous (that is, acquire or dock) with a failed P/L for repair or recovery.

Certain of the above probabilities are not applicable for certain scenarios and others have meanings only to the internal workings of the model. These conditions are summarized in Table C-4 (na = not applicable).

Table C-5 shows the input menu for the reliability data for Scenario 1 (direct placement using ground based assets). (Note that the menu extends from 1 to 15 years, but only a few years are shown in this table.

4.4.2 Launch Delay Data

The delay data indicates the time delay (years) that is likely to result from a failure. The delay data is specified as a range of uncertainty and

Rel.	Transportation Scenario								
Item	1	2	3	4	5	6	7	8	9
1	–	–	–	–	–	–	na	na	–
2	–	–	–	–	–	–	na	na	–
3	–	–	–	–	–	–	na	na	–
4	–	–	–	–	–	–	na	na	–
5	–	–	–	–	–	–	–	–	–
6	–	–	–	–	1.0	–	na	–	na
7	–	–	–	–	–	–	–	–	–
8	–	–	1.0	1.0	–	–	na	na	–
9	–	–	na	na	–	–	na	na	–
10	na	–	na	na	na	–	na	–	–
11	na	–	–	–	na	–	–	–	–

Table C–4: Applicability Matrix: Reliability Data

Transportation Scenarios

	Year			
Probability of	1	2	...	15
LVS1 success	.99	.99		.99
LVS2 Recv; LVS1 fail	.00	.00		.00
LVS2 succ; LVS1 succ	.98	.98		.98
LVS2 recv; LVS2 abor	.00	.00		.00
OTV checkout succ	1.00	1.00		1.00
LVS2 recv; LVS2 succ	.00	.00		.00
OTV transfer succ	.97	.97		.97
P/L checkout in LEO	1.00	1.00		1.00
P/L OK in GEO	.91	.91		.91
OTV rec; OTV succ	.00	.00		.00
OTV rendezvous	.00	.00		.00

Table C–5: Reliability Data, Scenario 1 [4a]

 c - 3

Delay Item	Transportation Scenario								
	1	2	3	4	5	6	7	8	9
i.	–	–	–	–	–	–	na	na	–
ii.	–	–	–	–	–	–	na	na	–
iii.	–	–	–	–	–	–	–	–	–
iv.	–	–	na	–	–	–	na	na	–
v.	–	–	–	–	–	–	–	–	–
vi.	–	–	na	na	–	–	na	na	–

Table C–6: Applicability Matrix for Delay Data

the form of the uncertainty. The following six delays may be considered:

i. Delay caused by LVS1 failures (including stand-down and rescheduling).

ii. Delay caused by LVS2 failure (including stand-down and rescheduling).

iii. Delay caused by OTV checkout failure (including servicing and rescheduling of launch).

iv. Delay caused by P/L checkout failure (including servicing and rescheduling of launch).

v. Delay caused by OTV failure (including stand-down and rescheduling).

vi. Delay caused by P/L failure (including stand-down and rescheduling).

Not all of these delays are applicable for each transportation scenario. Their applicability is summarized in Table C-6 (na = not applicable).

The following specific delay data is required (with the exceptions indicated in Table C-6) for each transportation scenario:

12. **MAXIMUM DELAY (YRS).** The maximum estimated delay that might result from each of the six indicated types of failures (years).

13. **MINIMUM DELAY (YRS).** The minimum estimated delay that might result from each of the six indicated types of failures (years).

14. **DELAY UNCERT PROF.** The ID of the applicable uncertainty profile that describes the form of the uncertainty within the identified range of uncertainty.

The time delay associated with testing a P/L that has been successfully placed into final P/L orbit may also be specified.

15. **P/L START DELAY (YRS).** The time (yrs) associated with the testing of a P/L that has been successfully placed into final orbit before the P/L can be considered as usable.

Table C-7 shows the input menu for the delay data for Scenario 1 (direct placement using ground based assets).

4.4.3 Launch Cost Data

Various cost data is required for each scenario. The data consists of seven parts:

- Launch cost from earth to LEO
- Return cost from LEO to earth
- OTV cost from LEO to GEO
- OTV cost from GEO to LEO
- P/L repair cost for checkout failure
- P/L repair cost for payload failure
- OTV cost for checkout failure

The first four cost items are specified for each year, thus allowing cost to change with time.

These are described below and are considered as uncertainty variables with each requiring the specification of maximum and minimum values together with the identity of the desired uncertainty profile.

Launch Cost from Earth to LEO

16. **MAXIMUM (M$).** The maximum estimated cost ($ millions) of transportation.

17. **MINIMUM (M$).** The minimum estimated cost ($ millions) of transportation.

	Delay Type					
	LVS1 i.	LVS2 ii.	OTV C iii.	P/L C iv.	OTV v.	P/L vi.
Max delay (yr)	1.5	1.5	.8	.8	1.5	1.5
Min delay (yr)	1.0	1.0	.5	.5	1.0	1.0
Delay uncert prof	2	2	2	2	2	2
P/L start delay (yr)	0.3	–	–	–	–	–

Table C–7: Delay Data Menu, Scenario 1 [4b]

Scenario	Payload Items Delivered to LEO
1	P/L, OTV
2	P/L 2, OTV, OMV
3	OTV, OMV, servicer, repair kit
4	OTV and OMV
5	P/L
6	P/L 2
7	Repair kit
8	–
9	Initial P/L to inventory and repair kit.

Table C–8: Earth-LEO Launch Items

Scenario	Payload Items, Return to Earth
1	OTV
2	P/L 1, OTV, OMV
3	OTV, OMV, servicer, and repair kit.
4	P/L, OTV, OMV
5	–
6	P/L 1
7	Repair kit
8	P/L
9	Repair kit

Table C–9: LEO-Earth Return Items

18. **PROFILE (ID).** The uncertainty profile ID to be associated with the launch cost range of uncertainty.

Table C-8 gives the items to be included in the determination of the launch cost from Earth to LEO.

Return Cost from LEO to Earth

19. **MAXIMUM (M$).** The maximum estimated cost ($ millions) of transportation.

20. **MINIMUM (M$).** The minimum estimated cost ($ millions) of transportation.

21. **PROFILE (ID).** The uncertainty profile ID to be associated with the launch cost range of uncertainty.

Table C-9 gives the items to be included in the determination of the return cost from LEO to earth.

OTV Cost from LEO to GEO

22. **MAXIMUM (M$).** The maximum estimated cost ($ millions) of transportation from LEO to GEO.

23. **MINIMUM (M$).** The minimum estimated cost ($ millions) of transportation from LEO to GEO.

24. **PROFILE (ID).** The uncertainty profile ID to be associated with the cost of transferring from LEO to GEO.

Table C-10 gives the items to be included in the determination of the transfer cost from LEO to GEO.

OTV Cost from GEO to LEO

Scenario	Payload Items, LEO to GEO
1	P/L
2	P/L, OMV
3	Repair kit, OMV, servicer
4	OMV
5	P/L
6	P/L, OMV
7	Repair kit, OMV, servicer and repair kit.
8	OMV
9	P/L 2, OMV

Table C-10: LEO - GEO Launch Items

Scenario	Payload Items, GEO to LEO
1	-
2	P/L, OMV
3	Repair kit, OMV, servicer
4	P/L, OMV
5	-
6	P/L, OMV
7	Repair kit, OMV, servicer
8	P/L, OMV
9	P/L 1, OMV

Table C-11: GEO to LEO Payload Items

25. **MAXIMUM (M$).** The maximum estimated cost ($ millions) of transportation from GEO to LEO.

26. **MINIMUM (M$).** The minimum estimated cost ($ millions) of transportation from GEO to LEO.

27. **PROFILE (ID).** The uncertainty profile ID to be associated with the cost of transferring from GEO to LEO.

Table C-11 gives the items to be included in the determination of the transfer cost from GEO to LEO.

P/L Repair Cost for Checkout Failure

28. **MAXIMUM (%).** Maximum estimated cost of repairing a P/L checkout failure (expressed as a % of P/L unit recurring cost).

29. **MINIMUM (%).** Minimum estimated cost of repairing a P/L checkout failure (expressed as a % of P/L unit recurring cost.

30. **PROFILE (ID).** The uncertainty profile ID to be associated with the cost of repairing a checkout failure.

The P/L repair cost for checkout failure data need only be provided for scenarios 1, 2, 5 and 6.

P/L Repair Cost for P/L Failure

31. **MAXIMUM (%).** Maximum estimated cost of repairing a P/L failure (expressed as a % of P/L unit recurring cost).

32. **MINIMUM (%).** Minimum estimated cost of repairing a P/L failure (expressed as a % of P/L unit recurring cost).

33. **PROFILE (ID).** The uncertainty profile ID to be associated with the cost of repairing a P/L failure.

The P/L repair cost for P/L failures data need not be provided for scenarios 1 and 5.

OTV Cost for Checkout Failure

34. **MAXIMUM (%).** Maximum estimated cost of repairing an OTV checkout failure (expressed as a % of OTV transfer cost from LEO to GEO).

35. **MINIMUM (%).** Minimum estimated cost of repairing an OTV checkout failure (expressed as a % of OTV transfer cost from LEO to GEO).

36. **PROFILE (ID).** The uncertainty profile ID to be associated with the cost of repairing an OTV checkout failure.

Table C-12 shows the input menu for the launch cost data for Scenario 1 (direct placement using ground based assets). (Note that the menu extends from 1 to 15 years, but only a few years are shown in this table.)

	Year		
	1	2 ...	15
Launch: earth to LEO			
Maximum (M$)	37.0	37.0	37.0
Minimum (M$)	37.0	37.0	37.0
Profile (ID#)	1	1	1
Return: LEO to earth			
Maximum (M$)	0.0	0.0	0.0
Minimum (M$)	0.0	0.0	0.0
Profile (ID#)	1	1	1
OTV: LEO to GEO			
Maximum (M$)	9.5	9.5	9.5
Minimum (M$)	9.5	9.5	9.5
Profile (ID#)	1	1	1
OTV: GEO to LEO			
Maximum (M$)	0.0	0.0	0.0
Minimum (M$)	0.0	0.0	0.0
Profile (ID#)	1	1	1

P/L Repair Cost for Checkout Failure	
Maximum (%)	0.0
Minimum (%)	0.0
Profile (ID#)	13

P/L Repair Cost for P/L Failure	
Maximum (%)	0.0
Minimum (%)	0.0
Profile (ID#)	1

OTV Repair Cost for Checkout Failure	
Maximum (%)	0.0
Minimum (%)	0.0
Profile (ID#)	13

Table C–12: Launch Cost Data, Scenario 1 [4c]

Unit Recurring Cost	
Maximum (M$)	54.3
Minimum (M$)	54.3
Profile (ID#)	16
Non-Recurring Cost	
Maximum (M$)	6.0
Minimum (M$)	6.0
Profile (ID#)	1

Table C–13: Payload Cost Data Menu [13]

4.5 Payload Cost Data [13]

Payload (P/L) cost data consists of specifying unit recurring cost and nonrecurring costs as ranges of uncertainty and the form of the uncertainty. Learning rates and cost spreading functions are considered in Paragraphs C-4.2 and C-4.15.2 respectively. It is assumed that the business venture will utilize a single P/L configuration for all P/Ls within the business. Table C-13 shows the input menu for the P/L cost data.

4.5.1 Unit Recurring Cost

1. **MAXIMUM (M$).** Maximum estimated unit recurring cost ($ million) of P/L first unit cost.

2. **MINIMUM (M$).** Minimum estimated unit recurring cost ($ million) of P/L first unit cost.

3. **PROFILE (ID).** The uncertainty profile ID to be associated with the unit P/L recurring cost.

4.5.2 Non-Recurring Costs

4. **MAXIMUM (M$).** Maximum estimated nonrecurring cost ($ million) associated with the P/L.

5. **MINIMUM (M$).** Minimum estimated nonrecurring cost ($ million) associated with the P/L.

6. **PROFILE (ID).** The uncertainty profile ID to be associated with the P/L nonrecurring cost.

4.6 Insurance Data [14]

Insurance may be considered for launch operations (i.e. Earth to LEO), transfer operations (i.e. LEO to GEO), P/L checkout in LEO, and P/L start-up. Each of these may be considered separately with the cost of the insurance established as the expected loss (of each of the operations), taking into account all of the failure recovery paths and the associated probabilities of success, and the specific operations and costs at risk, multiplied by an insurance factor or multiplier that includes insurer cost margins and fees. A multiplier of 1.5, for example, provides a cost of insurance that is 1.5 times the expected loss.

The insurance data has two parts:

- Insurance indicator
- Insurance factors

The insurance data is specified for each of the nine scenarios. Table C-14 shows the input menu for the insurance data.

4.6.1 Insurance Indicator

(1 = Insurance; 0 = No Insurance.)

1. **LAUNCH.** Indicator of whether or not launch insurance will be taken.
2. **TRANSFER.** Indicator of whether or not transfer insurance will be taken.
3. **P/L CHECKCUT.** Indicator of whether or not P/L checkout insurance will be taken.
4. **P/L START-UP.** Indicator of whether or not P/L start-up insurance will be taken.

4.6.2 Insurance Factors

(Factor is multiplier of the expected loss.)

5. **LAUNCH.** Insurance multiplier of expected loss resulting from launch failures.
6. **TRANSFER (LEO TO GEO).** Insurance multiplier of expected loss resulting from transfer operation failures where transfer is from LEO to GEO.
7. **TRANSFER (GEO TO LEO).** Insurance multiplier of expected loss resulting from transfer operation failures where transfer is from GEO to LEO.
8. **P/L CHECKOUT.** Insurance multiplier of expected loss resulting from P/L checkout failure.
9. **P/L START-UP.** Insurance multiplier of expected loss resulting from P/L start-up failure.

4.7 Transponder Data [15]

The spacecraft may consist of both narrow and wide band transponders that may operate in two different frequency bands (for example, C and Ku bands). Within each of these frequency bands there may be a number of groups of transponders (maximum of 5) with a specified number of active transponders per group (maximum of 25) and a specified number of spare transponders per group (maximum of 10).

The reliability characteristics of each of these transponders is described in terms of random and wearout phenomena. Data for both the narrow and wide-band transponders is similar and consists of six items:

1. **NO OF GROUPS.** Number of groups of transponders within the frequency band. It is assured that spare transponders within a group may replace any of the active transponders within the group.
2. **NO TRANS/GRP.** Number of active transponders per group.
3. **SPARE TRANS/GRP.** Number of spare transponders provided initially per group. As active transponders fail these spares are then utilized.
4. **MEAN TIME FAIL (YR).** Mean time-to-failure (year) of a transponder.

Insurance Indicator (1=yes, 2=no insure)	Transportation Scenario								
	1	2	3	4	5	6	7	8	9
Launch	1	1	1	1	1	1	1	1	1
Transfer	1	1	1	1	1	1	1	1	1
P/L checkout	1	1	1	1	0	0	1	1	1
P/L startup	1	1	1	1	1	1	1	1	1

Insurance Factors (Mult. of exp. loss)	Transportation Scenario								
	1	2	3	4	5	6	7	8	9
Launch	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
Transfer (LEO to GEO)	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
Transfer (GEO to LEO)	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
P/L checkout	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
P/L startup	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25

Table C–14: Insurance Data Menu [14]

5. **EXP. WEAROUT (YRS).** Transponder expected wear-out time (year).

6. **STD WEAROUT (YRS).** The wear-out characteristics are described in terms of a normal distribution having a specified expected value (previous response) and standard deviation (current response) about the expected value.

Two additional items relate to the decision to replace a satellite with a specified number of failed transponders.

7. **W/N BAND REL IMP.** Relative importance of a wide-band transponder to a narrow-band transponder. This is used in making a relaunch decision based upon the number of narrow and wide band transponders that are still available for use. The relative importance may be based upon the relative revenue production of the wide and narrow band transponders.

8. **TRNSPNDR THRSHLD RELAUNCH.** Effective number of transponders (narrow band plus wide-band adjusted to reflect the relative importance) that triggers a relaunch. When the effective number of transponders falls below the specified value, the particular spacecraft will be replaced as soon as possible with another spacecraft. The specific time of replacement will depend upon launch delays and launch failures.

Table C-15 shows the input menu for the transponder data.

4.8 Spacecraft Subsystem Data [16]

In addition to individual transponders, the reliability characteristics of five major subsystems – power, on-orbit propulsion (AVCS), TT&C (tracking, telemetry and command), structure, and other – may be considered. These may be any subsystems, but with the general characteristics that the failure of one of these subsystems for all practical purposes makes the satellite inoperative and thus sets in motion the launch of a replacement. As with the transponders, the reliability characteristics of each subsystem are described in terms of random and wearout phenomena as follows:

1. **MEAN TIME FAIL (YR).** Mean time to failure (years) of each system.

2. **EXP WEAROUT (YRS).** Subsystem expected wear out time (years).

Narrow Band	
No. of groups	0
No. trans/grp	0
Spare trans/grp	0
Mean time fail (yr)	0
Exp. wearout (yr)	0
STD wearout (yr)	0
Wide Band	
No. of groups	1
No. trans/grp	24
Spare trans/grp	6
Mean time fail (yr)	60.0
Exp. wearout (yr)	10.0
STD wearout (yr)	1.0
Wide/Narrow Rel. Imp.	1
Trnspndr Thrshld Relaunch	
Satellite No. 1	17
Satellite No. 2	17
Satellite No. 3	17
Satellite No. 4	0
Satellite No. 5	0

Table C–15: Transponder Data Menu [15]

3. **STD WEAROUT (YRS).** Variability, expressed as the standard deviation, of wear out time (years) about the mean or expected value.

Table C-16 shows the input menu for the spacecraft subsystem data.

4.9 Transponder Demand Data [17–36]

Demand data must be provided for each year of the analysis, for narrow band and wide band transponders, for each satellite considered and for service type. (Items [17–21] refer to service type i., satellites 1 to 5 respectively. Items [22–26] refer to service type ii., satellites 1 to 5 respectively. Items [27–31] refer to service type iii., satellites 1 to 5 respectively. Items [32–36] refer to service type iv., satellites 1 to 5 respectively.)

The following four specific service types are considered:

i. **Protected Service.** Protection is provided through provision of spares and preemptible transponders.

ii. **Protected/Preemptible Service.** Protection is provided through available spares and preemptible transponders. This service may be preempted if protected users require transponders.

iii. **Unprotected/Non-Preemptible.** Replacement transponders are not guaranteed but service may not be interrupted to provide service for other users.

iv. **Preemptible - Not Protected.** May be preempted if required to provide service for protected users.

Table C-17 shows the input menu for the transponder demand data for service type (i.), satellite no. 1 (item [17]). All demand data items, [17] through [36], have the same format. The menu extends from 1 to 15 years.

	Subsystem				
	Power	AVCS	TT&C	Struct	Other
Mean time to failure (yr)	250.0	160.0	220.0	1000.0	1000.0
Expected wearout time (yr)	15.0	11.0	15.0	20.0	20.0
Standard deviation of wearout (yr)	1.0	0.5	1.0	1.0	1.0

Table C–16: Spacecraft Subsystem Data Menu [16]

	Year														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Narrow band															
Maximum demand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Minimum demand	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Uncert Profile (ID#)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wide band															
Maximum demand	0	0	0	17	17	17	17	17	17	17	17	17	17	17	17
Minimum demand	0	0	0	17	17	17	17	17	17	17	17	17	17	17	17
Uncert Profile (ID#)	0	0	0	1	3	8	14	9	8	8	7	7	7	7	7

Table C–17: Transponder Demand Data Menu (Service Type i., Satellite No. 1) [17]

4.9.1 Narrow Band Transponder Demand

1. **MAX DEMAND.** Maximum estimated demand for narrow band transponders for each year of the analysis (number of transponders).

2. **MIN DEMAND.** Minimum estimated demand for narrow band transponders for each year to the analysis (number of transponders).

3. **UNCERT PROFILE.** The name of the uncertainty profile to be associated with the narrow band transponder demand.

4.9.2 Wide Band Transponder Demand

4. **MAX DEMAND.** Maximum estimated demand for wide band transponders for each year of the analysis (number of transponders).

5. **MIN DEMAND.** Minimum estimated demand for wide band transponders for each year of the analysis (number of transponders).

6. **UNCERT PROFILE.** The name of the uncertainty profile to be associated with the wide band transponder demand.

4.10 Transponder Price Data [37–40]

Price data must be provided for both the narrow band and wide band transponders for each year of the analysis and for each of the four types of service (as designated above). (Item [40] refers to service type i., item [41] refers to service type ii., item [42] refers to service type iii., and item [43] refers to service type iv.) All pricing data is to be provided in thousands of dollars per year.

Table C-18 shows the input menu for the transponder price data for service type i. [37], "Protected Service". All price data items, [37] through [40] for the four transponder service types (see Paragraph C-4.9), have the same format. The menu extends from 1 to 15 years.

	Year														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Narr. band															
Max price	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Min price	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Uncrt prf.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wide band															
Max price	0	0	0	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400
Min price	0	0	0	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400	2400
Uncrt prf.	0	0	0	6	6	6	6	6	6	6	6	6	6	6	6

Table C–18: Transponder Price Data Menu (Service Type i.) [37]

4.10.1 Narrow Band Transponder Price

1. **MAX PRICE.** Maximum estimated price (thousands of dollars) for narrow band transponders per year for each year of the analysis.

2. **MIN PRICE.** Minimum estimated price (thousands of dollars) for narrow band transponders per year for each year of the analysis.

3. **UNCERT PROFILE.** The name of the uncertainty profile to be associated with the price for narrow band transponders.

4.10.2 Wide Band Transponder Price

4. **MAX PRICE.** Maximum estimated price (thousands of dollars) for wide band transponders per year for each year of the analysis.

5. **MIN PRICE.** Minimum estimated price (thousands of dollars) for wide band transponders per year for each year of the analysis.

6. **UNCERT PROFILE.** The name of the uncertainty profile to be associated with the price for wide band transponders.

4.11 Price Elasticity Data [41]

Price elasticity data must be provided for both the narrow and wide band services. The price elasticity is represented by the percent demand decrease resulting from a 25 percent price increase. Thus, when it is estimated that a 25 percent price increase will result in a 25 percent decrease in demand the price elasticity is one (i.e. unit elasticity). Table C-19 shows the form of the price elasticity data input menu.

% Demand Decrease Resulting from a 25% Price Increase	Narr. Band	Wide Band
i. Protected	0	25
ii. Protected/Preemptible	0	25
iii. Unprotected/Non-preempt.	0	25
iv. Preemptible	0	25

Table C–19: Price Elasticity Data Menu [41]

4.12 Correlation Data [42]

Because of the random sampling used to establish the value of the uncertainty variables (demand, price, G&A expense, etc.) for each year of the analysis, it is possible that unreasonable year-to-year fluctuations will occur in the values of these variables. To smooth out unwarranted fluctuations, year-to-year correlation coefficients have been introduced. The correlation coefficient relates the current year value of a variable to all previous year's values of the variable. A correlation coefficient of zero implies that there is no dependence on previous year's values, whereas a correlation coefficient of unity implies that this years deviation from the expected value (the result of a random sample) cannot exceed the previous year's deviation from its expected value.

1. **DEMAND DATA.** The correlation coefficient (in range of 0 to 1.0) must be specified for both the narrow and wide band demand for the (1) Protected, (2) Protected-Preemptible, (3) Unprotected-Nonpreemptible, and (4) Preemptible Services.

2. **PRICE DATA.** The correlation coefficient (in the range of 0 to 1.0) must be specified for both the narrow and wide band pricing for the (1) Protected, (2) Protected-Preemptible, (3) Unprotected-Nonpreemptible, and (4) Preemptible Services.

3. **S/C CONTROL OPERATIONS.** Correlation coefficient (in the range of 0 to 1.0) for annual spacecraft control operations.

4. **ENGINEERING EXPENSE.** Correlation coefficient (in the range of 0 to 1.0) for annual engineering expenses.

5. **R&D EXPENSE.** Correlation coefficient (in the range of 0 to 1.0) for annual R&D expenses.

6. **G&A EXPENSE.** Correlation coefficient (in the range of 0 to 1.0) for annual general and administrative expenses.

7. **OTHER CAPITAL EXPENDITURES.** Correlation coefficient (in the range of 0 to 1.0) for other capital expenditures.

Table C-20 shows the form of the correlation data input menu.

	Corr. Coeff.	
Type of Service	Narr. Band	Wide Band
Demand Data		
i. Protected	.0	.8
ii. Prot./Preempt.	.0	.8
iii. Unprot./Non-preempt.	.0	.8
iv. Preemptible	.0	.8
Price Data		
i. Protected	.0	.8
ii. Prot./Preempt.	.0	.8
iii. Unprot./Non-preempt.	.0	.8
iv. Preemptible	.0	.8

	Correlation Coefficient
S/C Control Operations	.8
Engineering Expense	.8
R&D Expense	.8
G&A Expense	.8
Other Capital Expenditures	.8

Table C–20: Correlation Data Menus [42]

4.13 S/C Control Operations [43]

Annual spacecraft control operations cost is computed as a percentage of annual revenue. The range of uncertainty (of the percentage amount) and the associated uncertainty profile is provided for each year of the analysis.

1. **MAX COST (%).** Maximum estimated annual spacecraft control operations cost expressed as a percentage of annual revenue.

2. **MIN COST (%).** Minimum estimated annual spacecraft control operations cost expressed as a percentage of annual revenue.

3. **UNCERT PROFILE.** The name of the uncertainty profile to be associated with the spacecraft control and operations cost.

Table C-21 shows the input menu for the spacecraft control operations cost [43]. The menu extends from 1 to 15 years.

4.14 Engineering, R&D, and G&A [44–46]

A common format and method is used for computing annual Engineering, R&D (Research and Development), and G&A (General and Administrative) Expenses. Therefore, only the Engineering expense data is described in detail. In all cases the expense is established as having both a fixed component (a dollar amount specified for each year of the analysis) and a variable component (a percentage of revenue where the percentage is specified for each year of the analysis). Both the fixed and variable components are considered as uncertainty variables. The annual expense is established as either the sum of the fixed and variable components or as the larger of the two components.

1. **MAX (K$).** Maximum estimated annual expense (fixed component) expressed as a dollar amount (in thousands of dollars).

2. **MIN (K$).** Minimum estimated annual expense (fixed component) expressed as a dollar amount (in thousands of dollars).

3. **UNCERT PROFILE.** The name of the uncertainty profile to be associated with the fixed component of the annual expense.

4. **MAX (%).** Maximum estimated annual expense (variable component) expressed as a percentage of revenue.

5. **MIN (%).** Minimum estimated annual expense (variable component) expressed as a percentage of revenue.

6. **UNCERT PROFILE.** The name of the uncertainty profile to be associated with the variable (%) component of the annual expense.

7. **SUM K$ & % AMTS.** When set equal to 0, the expense is the larger of the fixed and variable components. When set equal to 1, the expense is the sum of the fixed and variable components.

Tables C-22, C-23, and C-24 give the input data format menus for Engineering [44], R&D [45], and G&A [46] respectively. The input data covers 15 years.

4.15 Capital Expenditure Data [47]

Spacecraft recurring cost, launch cost and other launch related costs are treated as capital expenditures (i.e. depreciated). These costs occur as a result of satellite purchases and launches and therefore their timing depends upon the timing of launches which is basically demand driven.

There may be other capital expenditures that are not directly related to satellite launches (for example, the acquisition of TT&C ground terminals). These may be specified as dollar amounts (i.e. range of uncertainty) in the year of acquisition. Cost spreading is not imposed upon these expenditures which are depreciated starting in the year of acquisition.

4.15.1 Other Capital Expenditures

Table C-25 gives the input data menu for the other capital expenditure cost data (part of [47]). The data covers 15 years.

1. **MAX (K$).** Maximum estimated other capital expenditure each year of the analysis (thousands of dollars).

2. **MIN (K$).** Minimum estimated other capital expenditure each year of the analysis (thousands of dollars).

	Year														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Max cost (%)	0	0	0	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Min cost (%)	0	0	0	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Uncert prof.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table C–21: Spacecraft Control Operations Data Menu [43]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Max $k/yr	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900
Min $k/yr	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900
Uncrt prf	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Max %	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Min %	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Uncrt prf	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table C–22: Engineering Expense Data Menu [44]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Max $k/yr	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900
Min $k/yr	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900
Uncrt prf	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Max %	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Min %	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Uncrt prf	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table C–23: R&D Expense Data Menu [45]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Maximum $k/yr	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
Minimum $k/yr	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
Uncert profile	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Maximum %	.0	.0	.0	7.3	1.3	.8	.8	.6	.6	.7	.8	1.0	1.0	1.4	2.9
Minimum %	.0	.0	.0	7.3	1.3	.8	.8	.6	.6	.7	.8	1.0	1.0	1.4	2.9
Uncert profile	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table C–24: G&A Expense Data Menu [46]

	Year														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Max $k/yr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Min $k/yr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Uncert Profile	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table C–25: Other Capital Expenditures Data Menu [47a]

3. **UNCERT PROFILE.** The name of the uncertainty profile to be associated with each year's other capital expenditures.

4.15.2 Cost Spreading Functions

Cost spreading functions may be imposed upon launch cost, insurance cost, spacecraft unit recurring cost and nonrecurring costs. The cost spreading is performed in two different ways: in relative time (i.e. relative to when launches occur) and in absolute time. Launch, insurance and spacecraft recurring cost are spread backward in time relative to the year of launch. Thus, year 1 is the year that a launch takes place, year 2 is the year prior to launch, year 3 is two years prior to launch, etc. Nonrecurring costs are spread in absolute time with a specified percentage of the nonrecurring costs occurring in year 1, year 2, etc. of the analysis.

4. **LAUNCH COST.** The percentage of the launch cost spent each year relative to the year of launch. Year 1 is the year of launch, year 2 is the year prior to launch, etc.
5. **INSURANCE.** The percentage of the insurance cost spent each year relative to the year of launch. Year 1 is the year of launch, year 2 is the year prior to launch, etc.
6. **S/C RECUR COST.** The percentage of the spacecraft recurring cost spent each year relative to the year of launch. Year 1 is the year of launch, year 2 is the year prior to launch, etc.
7. **NONRECUR COST.** The percentage of the nonrecurring cost spent each year with year 1 being the first year of the analysis, year 2 the second year of the analysis, etc.

Table C-26 shows the input menu for the spacecraft subsystem data. The data covers the five years prior to launch (beginning with the launch year).

	Year				
	1	2	3	4	5
Launch cost (%/yr)	0	50	30	20	0
Insurance (%/yr)	10	70	0	20	0
S/C recur cost (%/yr)	10	20	40	30	0
Non-recur cost (%/yr)	40	40	20	0	0

Table C–26: Cost Spreading Functions [47b]

4.16 Uncertainty Profile Data [48]

Table C-27 gives twenty different uncertainty profile data. The uncertainty profiles represent the probability density functions that may be used for one or more of the uncertainty variables. They represent the probability distributions in the range of uncertainty. The range ot uncertainty is in turn segmented into five equal intervals. Thus, for Uncertainty Profile 1 there is a 0.50 chance of selecting a value in the first of the five equal intervals, 0.25 chance of selecting a value in the second of the five equal intervals, etc. Linear interpolation is used to select a specific value within each interval.

All of the uncertainty profile data may be changed to create new uncertainty profiles. Caution: each row must add to unity! In other words, the probabilities associated with each profile must add to 1.00. Twenty uncertainty profiles are stored in the data base. However, a total of thirty (30) profiles are available for use with profiles 21 to 30 being mirror images of profiles 1 through 10, respectively.

4.17 Repair/Replace Decisions [49]

Repair and replacement decisions data represents the probability that a failed satellite is not repairable. It is assumed that this data is known before a repair/replace mission is launched. In the event of non-repairability, there is an immediate launch of a replacement satellite. As shown in Table C-28, the data is specified for each scenario and each year. Values must be in the range of 0.0 to 1.0, with 1.0 indicating the satellite is not repairable and 0.0 indicating that whenever a satellite fails, it can be repaired.

Profile I. D.	Uncertainty Profile Data Profile Interval 1	2	3	4	5
1	.50	.25	.15	.07	.03
2	.30	.25	.20	.15	.10
3	.30	.30	.20	.13	.07
4	.35	.40	.15	.07	.03
5	.21	.32	.27	.15	.05
6	.23	.30	.23	.16	.08
7	.25	.35	.25	.10	.05
8	.16	.49	.24	.09	.02
9	.12	.32	.32	.17	.07
10	.15	.34	.37	.12	.02
11	.20	.20	.20	.20	.20
12	.15	.22	.26	.22	.15
13	.10	.25	.30	.25	.10
14	.08	.25	.34	.25	.08
15	.05	.25	.40	.25	.05
16	.10	.20	.40	.20	.10
17	.03	.30	.34	.30	.03
18	.05	.20	.50	.20	.05
19	.03	.20	.54	.20	.03
20	.03	.07	.80	.07	.03

Table C–27: Uncertainty Profile Menu [48]

Scenario	Year 1	2	...	15
1	.15	.15		.15
2	.15	.15		.15
3	.15	.15		.15
4	.15	.15		.15
5	.15	.15		.15
6	.15	.15		.15
7	.15	.15		.15
8	.15	.15		.15
9	.15	.15		.15

Table C–28: Repair Replacement Decisions [49]

5 Example of Input/Output

5.1 Input Data for Model

The input data for the Model follows the menus described in Subsection C-4 and illustrated in the tables of Subsection C-4. The entries in Tables C-1 through C-28 refer to a standard satellite (1995 hybrid design) being launched from earth to GEO orbit via Scenario 1.

5.2 Output from Model

Tables C-29 through C-33 illustrate the Model outputs:

1. Proforma income statements (C-29 and C-30).
2. Cash flow statements (C-32 and C-33); Net Present Value for different discount rates (C-31).
3. Event statistics (C-34).

All entries in these tables are expected values except those which are standard deviations. All results presented for each case are based upon simulating the business venture 1,000 times (i.e. 1,000 Monte Carlo simulation runs were performed).

5.2.1 Proforma Income Statement

Tables C-29 and C-30 illustrates the Proforma Income Statement which covers a 15 year period. The business scenario is to provide communications services with three satellites launched in the 4th, 5th and 6th years of a business venture. The initial satellites are placed into orbit via Scenario 5 (satellites are delivered to the Space Station and placed into GEO with a space-based orbital transfer vehicle).

The satellites are retrievable and repairable with a probability of repair specified via input data. A satellite previously and successfully placed into orbit which fails due to random or wearout failures is returned to the Space Station for repair and placement into inventory with a replacement satellite placed into orbit prior to the return of the failed satellite.

	Year							
	1	2	3	4	5	6	7	8
Protected	0	0	0	30,327	90,915	138,371	121,584	121,798
Protected/Preemptible	0	0	0	2,676	3,503	8,443	9,913	10,138
Unprot./non-preemptible	0	0	0	0	0	0	0	0
Preemptible	0	0	0	1,487	788	2,147	5,507	5,558
Total Revenue	0	0	0	34,483	95,206	148,960	137,005	137,360
Standard deviation	0	0	0	9,344	15,418	12,760	6,983	5,833
Launch operations	0	0	0	6,143	12,302	18,627	18,837	19,263
Launch insurance	0	0	0	802	1,559	2,299	2,313	2,341
Satellite	0	0	0	7,086	13,509	19,560	19,600	19,655
Other	0	0	0	0	0	0	0	0
Depreciation expense	0	0	0	14,031	27,370	40,485	40,750	41,258
S/C control operations	0	0	0	138	381	596	548	549
P/L maintenance	0	0	0	0	18	152	210	421
OTV maintenance	0	0	0	0	0	0	0	0
Space Station lease	0	0	0	1,500	1,500	1,500	1,500	1,500
Engineering expense	1,000	1,000	1,000	1,000	1,908	2,979	2,740	2,747
Research & development	1,000	1,000	1,000	1,000	1,908	2,979	2,740	2,747
Total operations exp. ($)	2,000	2,000	2,000	17,663	33,086	48,692	48,488	49,223
Stnd. deviation	0	0	0	37	902	2,383	2,978	4,167
Gross Margin ($)	-2,000	-2,000	-2,000	16,820	62,120	100,263	88,517	88,136
Standard deviation	0	0	0	9,307	14,981	13,417	8,317	8,963
S/C nonrecurring cost	2,400	2,400	1,200	0	0	0	0	0
G & A expense	500	500	500	3,018	1,738	1,632	1,596	1,324
Debt service expense ($)	0	4,243	12,850	24,670	32,887	33,825	27,001	18,662
Before tax profit	-4,900	-9,143	-16,550	-10,868	27,496	64,753	59,921	68,150
Income tax	-1,891	-3,529	-6,388	-4,195	10,613	24,995	21,129	26,306
Investment tax credit	0	0	0	0	0	0	0	0
After tax profit ($)	-3,009	-5,614	-10,162	-6,673	16,882	39,758	36,791	41,844
Standard deviation	0	231	317	5,172	9,391	9,008	6,491	7,356
Return on assets (%)	-8	-5	-5	-2	6	14	16	21
Standard deviation	1	0	0	2	3	3	3	5
Return on sales (%)	0	0	0	-14	15	26	27	30
Standard deviation	0	0	0	14	18	6	4	5

Table C–29: Proforma Income Statement (1/2)

	Year						
	9	10	11	12	13	14	15
Protected	121,868	121,901	121,767	121,811	120,133	104,359	92,583
Protected/Preemptible	10,114	10,138	10,067	10,104	8,790	2,458	1,676
Unprot./non-preemptible	0	0	0	0	0	0	0
Preemptible	5,619	5,632	5,593	5,614	4,863	1,310	897
Total Revenue	137,601	137,671	137,426	137,529	133,786	108,128	95,156
Standard deviation	5,636	5,213	6,263	5,847	8,819	19,143	25,167
Launch operations	19,515	19,810	13,968	8,078	2,078	4,560	10,280
Launch insurance	2,359	2,377	1,594	854	136	286	648
Satellite	19,715	19,747	12,702	6,320	329	604	1,462
Other	0	0	0	0	0	0	0
Depreciation expense	41,588	41,934	28,265	15,252	2,542	5,450	12,389
S/C control operations	550	551	550	550	535	433	381
P/L maintenance	243	281	289	263	259	1,916	4,694
OTV maintenance	0	0	0	0	0	0	0
Space Station lease	1,500	1,500	1,500	1,500	1,500	1,500	1,500
Engineering expense	2,752	2,753	2,749	2,751	2,676	2,165	1,916
Research & development	2,752	2,753	2,749	2,751	2,676	2,165	1,916
Total operations exp. ($)	49,386	49,772	36,101	23,066	10,187	13,627	22,797
Stnd. deviation	4,078	4,471	4,803	4,965	5,036	8,168	8,058
Gross Margin ($)	88,216	87,899	101,325	114,463	123,599	94,500	72,359
Standard deviation	7,898	8,006	9,064	8,731	10,618	20,311	25,886
S/C nonrecurring cost	0	0	0	0	0	0	0
G & A expense	1,326	1,464	1,599	1,875	1,838	2,014	3,260
Debt service expense ($)	9,854	417	-9,657	-19,385	-27,910	-35,474	-42,374
Before tax profit	77,036	86,017	109,383	131,973	146,670	127,961	114,474
Income tax	29,736	33,203	42,222	50,941	57,773	49,393	43,029
Investment tax credit	0	0	0	0	0	0	0
After tax profit ($)	47,300	52,815	67,161	81,031	91,898	78,568	68,445
Standard deviation	6,968	7,339	8,157	8,184	8,928	12,924	15,158
Return on assets (%)	30	44	69	81	76	60	58
Standard deviation	6	10	16	18	20	24	23
Return on sales (%)	34	38	49	59	69	73	75
Standard deviation	4	5	5	5	5	9	21

Table C–30: Proforma Income Statement (2/2)

It is assumed that the transportation system and the OTV operations are not part of the communications satellite business venture. The business venture pays fees for services rendered and does not pay directly for such items as OTV maintenance and repair (this is assumed to be included in the cost of the OTV). The DOMSAT III Model allows costs, transponder demand, transponder prices, and other variables to be considered as uncertainty variables (i.e. ranges of uncertainty and associated probability density functions). Because many of these variables were held constant from case to case, only deterministic values were utilized so as not to mask the true differences resulting from the use of different transportation scenarios and satellite configurations. Uncertainty variables were considered for the time delays resulting from transportation system and satellite failures since these are directly related to the transportation scenarios.

Revenue is disaggregated into four service types, three of which are considered. Launch operations, launch insurance, satellite unit recurring costs and other capital expenditure items are depreciated. Launch insurance is considered separately for launch (to LEO), satellite checkout in LEO, OTV transfer of satellite to GEO, and satellite initial operational success. Any or all of these insurance options may be taken with the cost of insurance being a multiple (as specified via the input data) of the expected loss as determined by reliability considerations and failure – recovery paths.

If failures occur during launch, delays are introduced before another satellite can be launched. During this time, additional satellite failures may occur with consequent revenue reduction. Other expense items considered include the following:

- Satellite control operation,
- Payload maintenance expense (repair of satellite failures and repair of satellites that do not check-out properly in LEO prior to delivery to GEO).
- OTV maintenance expense (in keeping with the above assumptions, this is zero for the current analyses).
- Space Station lease expense for storing a satellite in inventory.
- Engineering and R&D expenses.

These latter two expenses are assumed to be a fixed annual amount or a percentage of revenue, whichever is the larger.

Satellite nonrecurring cost is assumed to be expensed. General and Administrative (G&A) expense is assumed to be a fixed annual amount plus a percentage of revenue. Debt service expense is based upon the prior year's indebtedness (negative of the cumulative cash flow at any point in time). After tax profit is computed based upon an assumed corporate tax rate constant over the 15 year time horizon considered for the business plan.

5.2.2 Cash Flow Statement

Tables C-32 and C-33 illustrate the Cash Flow projection. Cash inflow is the sum of after tax profit, increase in payables, decrease in receivables, decrease in cash (a specified percentage of operating expenses) and depreciation. Cash outflow is the sum of losses, decrease in payables, increase in receivables, increase in cash and capital expenditures. Net cash flow is the difference between cash inflow and outflow. Indebtedness is the negative of the cumulative cash flow. Thus when indebtedness is positive, the firm is in debt (i.e. cumulative cash outflows exceed cumulative cash inflows) and when indebtedness is negative the firm is out of debt. The point in time when the indebtedness passes through zero is the payback period (for the case illustrated, the payback occurs in the 9th year).

Net present value is established at five specified discount rates, and is given in Table C-31. The net present value is considered in two parts:

A. The net present value contribution of the annual cash flow during the 15 year planning horizon.

B. The net present value contribution of the last year's cash flow if this were maintained

	Year				
	1	2	3	4	5
Discount Rate (%)	10	15	20	25	40
Net Present Value (A)	57,518	-18,395	-59,029	-80,116	-93,991
Net Present Value (B)	150,162	51,391	20,356	8,828	1,008
Net Present Value ($)	207,680	32,997	-38,673	-71,288	-92,983
Standard Deviation	64,204	27,461	16,456	11,928	6,096

Table C–31: Net Present Value for Different Discount Rates

for all time. This is referred to as the infinite horizon contribution.

The total net present value is the sum of the two components. The net present value probability distribution is specified by its expected value and standard deviation since it is a good approximation to assume "normality". The net present value probability distributions at the five different discount rates are used to establish the probability distribution of the discounted return on investment (ROI).

5.2.3 Event Statistics

Tables C-34 and C-35 indicate the event statistics in the form of the probability of the indicated quantities (i.e., the probability density function) for years 10 and 15. (The event statistics are given for every year, only sample outputs for two years are given in the tables.) The event statistics are developed separately for the specified placement and repair scenarios. Indicated are the identities of the specific scenarios utilized in the year being displayed. (For example, placement flights are performed using Scenario 5 and repair flights are performed using Scenario 9. In the event of repair flight failure, the placement scenario is used and the results incorporated in the placement section of the table.) For placement flights, Table C-34 indicates the probability of the number of launches paid for (if a launch failure occurs that is covered by insurance, only the initial flight is included in the figure), satellites serviced (correcting checkout failures) and repaired (correcting satellite failures that occur after the satellite has been placed into service), and OTVs paid for (if an OTV failure occurs that is covered by insurance, only the initial flight is included in the figure). For repair flights, Table C-34 indicates the probability of the number of launches paid for, satellites serviced, satellites repaired and OTVs paid for.

Referring to Table C-35, a 100 in the "0" row indicates that there is a 100 % chance that no events will occur, a 43 in the row, a 44 in the "1" row and a 13 in the "2" row indicates that there is a 43 % chance of no events, a 44 % chance of exactly one event, and a 13 % chance of exactly 2 events occurring. Average (expected) values and standard deviations are presented for each of the considered events (i.e., columns).

5.2.4 Results of Example

Case 5 is based upon the use of OTVs that are based on the Space Station. New satellites are delivered to the Space Station and placed into GEO via the space-based OTVs. A modular designed satellite is utilized. When satellites fail a spare satellite maintained in inventory on the Space Station is placed into GEO and the failed satellite returned via the OTV to the Space Station where it is repaired and placed into inventory for use when the next failure occurs. As in Case 4, consideration is given to the fact that it is unlikely that all satellite failures can be repaired. When satellite failures are not repairable, new satellites are placed into orbit via the use of the Space Station and the OTV.

	Year							
	1	2	3	4	5	6	7	8
After tax profit	0	0	0	0	17,684	39,829	36,820	41,860
Increase in payables	3,604	3,416	2,607	12	2	0	14	19
Decrease in receivables	0	0	0	0	4	6	2,291	146
Decrease in cash	0	0	0	137	387	455	177	138
Depreciation	0	0	0	14,031	27,370	40,485	40,750	41,258
Total cash inflow ($)	3,604	3,416	2,607	14,180	45,448	80,776	80,052	83,421
Loss	3,009	5,614	10,162	6,673	802	71	29	16
Decrease in payables	0	0	0	757	2,142	2,518	977	763
Increase in receivables	0	0	0	5,760	10,144	8,983	295	205
Increase in cash	651	617	471	2	0	0	2	3
Capital expenditures	38,516	75,428	99,431	75,686	40,887	7,167	2,942	2,356
Total cash outflow ($)	42,176	81,659	110,064	88,877	53,975	18,738	4,246	3,344
Net cash flow ($)	-38,572	-78,244	-107,458	-74,697	-8,527	62,037	75,806	80,077
Standard deviation	3,419	1,338	3,453	6,994	12,417	12,033	11,549	9,477
Indebtedness ($)	38,572	116,816	224,274	298,971	307,438	245,461	169,656	89,579
Standard deviation	3,419	4,687	3,341	7,576	19,188	28,920	36,912	42,562

Table C–32: Cash Flow Projection (1/2)

	Year						
	9	10	11	12	13	14	15
After tax profit	47,301	52,816	67,165	81,031	91,897	78,568	68,445
Increase in payables	21	21	110	427	179	244	0
Decrease in receivables	178	153	185	167	780	4,381	3,195
Decrease in cash	137	142	107	34	55	164	413
Depreciation	41,588	41,588	28,265	15,252	2,542	5,450	12,389
Total cash inflow ($)	89,226	95,064	95,832	96,911	95,453	88,807	84,443
Loss	0	0	4	0	0	0	0
Decrease in payables	758	783	594	190	304	910	2,286
Increase in receivables	219	165	144	184	155	96	1,029
Increase in cash	4	4	20	77	32	44	0
Capital expenditures	2,456	2,529	6,635	18,967	26,193	25,031	912
Total cash outflow ($)	3,436	3,480	7,397	19,418	26,684	26,081	4,227
Net cash flow ($)	85,789	91,584	88,435	77,493	68,769	62,726	80,216
Standard deviation	9,578	9,229	10,902	11,315	16,008	23,437	12,193
Indebtedness ($)	3,789	-87,795	-176,230	-253,723	-322,493	-385,219	-465,435
Standard deviation	47,251	51,721	55,459	56,974	59,152	60,474	61,606

Table C–33: Cash Flow Projection (2/2)

Number of Events	Probability of Indicated Events (%)							
	Placement Flights (Scenario 5)				Repair Flights (Scenario 9)			
	Launches Paid for	P/Ls Serviced	P/Ls Repaired	OTVs Paid for	Launches Paid for	P/Ls Serviced	P/Ls Repaired	OTVs Paid for
10	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
1	1	0	0	1	2	0	4	4
0	99	100	100	99	98	100	96	96
Average value	.0	.0	.0	.0	.0	.0	.0	.0
Standard deviation	.1	.0	.0	.1	.1	.0	.2	.2

Table C–34: Event Statistics (Year 10)

Number of Events	Probability of Indicated Events (%)							
	Placement Flights (Scenario 5)				Repair Flights (Scenario 9)			
	Launches Paid for	P/Ls Serviced	P/Ls Repaired	OTVs Paid for	Launches Paid for	P/Ls Serviced	P/Ls Repaired	OTVs Paid for
10	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
2	1	0	0	1	0	0	11	14
1	14	0	0	14	46	0	46	47
0	86	100	100	86	51	100	43	39
Average value	.2	.0	.0	.2	.5	.0	.7	.7
Standard deviation	.4	.0	.0	.4	.6	.0	.7	.7

Table C–35: Event Statistics (Year 15)

Appendix D
INSURANCE COMPANY INTERVIEWS

An evaluation is given based on the insurance industry interviews of potential on-orbit operations such as assembly of satellites, retrieval of ailing satellites, and repair at the Space Station and relaunch.

The discussion is organized into the following parts:

1. Specification of scenarios

2. Approach to interviews

3. Interview results

4. Summary of interviews

1 Specification of Scenarios

Two scenarios are proposed for evaluation by the insurance industry:

1. On-orbit assembly of satellites

2. On-orbit repair of ailing satellites

A primary driver to the viability of a scenario is the insurance implication. There are the following potential benefits of the scenarios:

- One major constraint on satellite design has historically been the shape, weight restrictions, and size of the payload area in the launch vehicle. Since satellites would be launched in components rather than as an assembled unit, the restrictions on satellite size, shape, and weight would now be driven only by satellite performance and economic considerations, not by the configuration and capabilities of launch vehicles.

- Satellites can be tested and deployed prior to transfer to their final orbit. This may greatly reduce the check out and operation risk of satellite launch.

- On-orbit failures may not be total losses. If proven cost effective, a satellite could be retrieved, repaired, and redeployed without having to return to earth.

- Aged satellites which would otherwise be written off may be candidates for overhaul and upgrade based on the cost and performance characteristics of each case.

1.1 Assembly at the Space Station

With this scenario, satellite components are launched to the Space Station via the Space Shuttle or expendable launch vehicle. They would then be assembled and tested at the Space Station and the fully assembled satellite would be transferred to its final orbit destination. The specific issues relating to this scenario are as follows:

- To reduce the launch shock risk, the components could be packaged in shock absorbing material during initial launch.

- In order to spread the launch risk for a satellite, its components could be launched on a number of launch vehicles. Certain standard components could also be stored on the space station for use during both assembly and repair.

- The assembly process would be designed to utilize the Space Station's automation and robotics capabilities to reduce the need for Space Station crew time.

- Assembled satellites would be tested and have their solar panels and antenna deployed at the Space Station.

- The fully deployed satellite would be transferred to its final orbit using a low thrust OTV.

1.2 Repair at the Space Station

Ailing satellites could be retrieved and brought to the Space Station for repair and then relaunched. This process would entail the following steps and issues:

- The capability for retrieval by an unmanned OTV (or another viable method) would be designed into the satellite prior to initial launch.

- The satellite would be retrieved from its existing orbit and brought to the Space Station. Any components needed to repair the satellite will either be in inventory at the Space Station or be transported from earth.

- The repair would benefit from modular satellite design and the use of automation and robotics on the Space Station.

- The repaired satellite is tested, deployed, and transferred back to its original orbit in the same manner as a newly assembled satellite.

2 Approach

The detailed approach used to gather the information from insurance industry executives and draw pertinent conclusions relied on the experience *The Egan Group* has in the satellite industry and included the following series of steps:

- Defining scenarios for assembly and repair of satellites at the Space Station.

- Defining the characteristics of satellites having the capability for retrievability, repair, and assembly on orbit.

- Developing an interview guide to assure that each interview covered the same points. The main focus of the interview was the effect on risk and insurance rates of assembling and repairing satellites on-orbit using Space Station facilities.

- Conducting interviews with at least one executive with each of five major firms involved in the brokerage or underwriting of space ventures. The firms interviewed are as follows:

  - Corron & Black, Inspace
  - Frank B. Hall Inc.
  - Marsh & McClennan Aviation and Aerospace Services
  - International Technology Underwriters
  - Johnson & Higgins, Space Systems Group

- Once the information was gathered we used our experience with the satellite industry and the space program in general to analyze the insurance industry input and draw conclusions.

3 Interview Results

There was a diversity of opinions on the potential effect of the scenarios on risk and insurance rates, and the economic feasibility of the scenarios. The discussion is divided into the responses to the two scenarios and a third paragraph on general issues raised during the interviews:

1. Assembly at the Space Station
2. Retrieval and Repair
3. General Issues

3.1 Assembly of Satellites

The effects of assembling satellites on the Space Station and then transporting them to their final orbit should be compared with the current practice of launching intact commercial satellites directly to their final orbit destination. Each approach has distinct stages where risks, and therefore insurance coverage and rates, are handled as discrete entities.

The opinions of the insurance industry executives on the effect of Space Station based assembly of satellites were generally favorable, but with some serious concerns on the technical feasibility and cost effectiveness of the initiative.

- The majority of those interviewed saw little effect on the rates for satellite launch from earth to the Space Station as compared to the current earth to low earth orbit. The same risks would be incurred under either approach. The expectation for this launch segment, however, is for insurance rates to fall in the long term to somewhere in the 5% to 10% range as reliability increases. There were some expected benefits that were discussed.

  - One executive saw the potential for increased insurance capacity since demonstrated reliability improvements may draw firms not normally associated with the space industry into the field to insure launches to LEO. This entry might not affect rates but would increase capacity and thereby help make the general placement of insurance easier.

  - Another executive was particularly interested in the capability of spreading the launch of components for a single satellite across multiple flights. This could provide a capability to limit the risk associated with any one launch. If a launch failed with only 30% of the components for a satellite, then it becomes a partial loss, not a total loss as would be the case if the entire satellite was on board.

- Work-in-Process coverage for the satellites will be required while the assembly process is conducted on the Space Station. Neither the cost nor the availability of this coverage is expected to be a major barrier to the scenario. However, the issues of general Space Station insurance and the capacity problems noted in this document under Paragraph III-5.3.3, General Issues, are pertinent to this issue.

- The ability to test the satellite and deploy solar arrays and antenna prior to transport to final orbit is considered one of the important benefits of this scenario and may lead to lower rates for satellite check out and initial operation coverage. However, two concerns must be raised.

  1. The advantage of on-orbit check out and testing of a satellite, while beneficial, represents only a small portion of the risk associated with placing satellites in orbit. The large majority of the risk is associated with the actual transportation of the satellite.

  2. The warranty issue for the work performed must also be addressed. If a satellite fails shortly after it is deployed on-orbit, the liability for that failure will have to be determined. If the government performs the assembly and test, they will most likely not accept any liability. If a commercial firm does the work, then they may be liable for negligence for work performed.

- The transport of fully deployed satellites to their final destination will present some technical issues which have to be addressed.

  - The reliability of the low-inertia OTV expected to transport satellites to their final orbit will have to be proved and may be a source of increased risk. It may ultimately not prove to be any more reliable than the current stages dedicated to that purpose.

  - A fully deployed satellite will have to be protected in some way against radiation during its transport through the Van Allen belts.

The assembly of satellites on-orbit is not without risks and technological challenges. However, the general opinion of the satellite insurers is that insurance rates will probably not pose a major barrier to the effort.

3.2 Retrieval and Repair of Satellites

The issue of retrieving, repairing, and redeploying satellites from the Space Station brought the widest range of opinions from the insurance industry. The responses ranged from those who were extremely doubtful about the economic feasibility of retrieving and redeploying satellites, to those who felt that certain situations presented ideal candidates for such activities. A summary of the responses includes:

- The cost of retrieving and redeploying the satellite must be brought down if this scenario is to be implemented. The retrieval cost will most likely far overweigh the actual cost of repair or upgrade at the Space Station. Of particular concern, as can be expected, is the cost of retrieval and return to geostationary orbit. Some of the interviewees felt that the transportation costs would be an insurmountable barrier to this effort.

- The technology for retrieving satellites must be proven before reduced rates could be realized.

- Recent history has proved to be both a positive and negative experience with the retrievability of satellites. It has been shown that some satellites can be retrieved with current technology. However, the retrieved satellites have not been able to be resold easily and other economic as well as relaunch problems have developed.

- High value commercial satellites are likely to be the main market for repair.

- The amount that a customer is willing to pay for retrieval and repair of a satellite may be driven not only by the cost of the satellite but also by factors such as:

  - Loss of revenues/market share during the period the satellite is inoperable.

  - Availability of alternative satellite capacity or other methods for providing the business services.

  - Lead time for launching a replacement satellite.

- The most widely touted benefit of the repair capability is that a single component failure may not mean the total loss of a multimillion dollar satellite. Because of this, insurance executives who assess rates based on maximum possible loss may start to assess certain segments of the launch process on a maximum probable loss (which is likely to be a lower figure) instead.

- An added risk is the risk incurred during the retrieval and repair process.

3.3 General Issues

A series of general issues were raised during our interviews that apply to both the assembly and repair of satellites on the Space Station:

- The entire question of Space Station third party liability insurance and workmen's compensation was not addressed here. This issue has and should be addressed for the Space Station as a whole, and not just for the satellite servicing facilities.

- The introduction of new technologies and processes may cause insurance rates to rise initially as the new methods are proving themselves.

- A concern was raised that if a large number of satellites are resident on the Space Station at one time in various stages of assembly and repair, then the insurance industry capacity may be overwhelmed by the large value of the number of satellites located at the same location.

- The satellite manufacturers will have to rethink the design of new satellites to implement a modular format to improve the ability to assemble and repair on the Space Station.

- The experience gained from the construction of the Space Station itself will be valuable in demonstrating the capability to assemble and repair satellites. This may convince insurers there is a reduced risk to the satellite during assembly and repair operations.

- The cost of storing standard satellite components on the Space Station may become a significant component of overall repair costs.

- A stable policy insuring access to Space Station facilities and resources will be required to promote this scenario.

- Some industry representatives expect there to be a trend towards lower cost satellites with co-orbiting backups. If this ultimately comes to fruition, then the market for on-orbit assembly and repair services may be reduced.

- In order for the Space Station itself, much less the satellite servicing facilities, to operate and prosper, the launch industry must show a dramatic increase in reliability. While insurance costs for satellite launch and operations currently comprise a large percentage of overall project costs, a demonstrated long term increased reliability may help to lower insurance costs to a point where their share of the total cost of a venture will shrink.

One of the most important points made in the interviews is that while the concept of Space Station based assembly and repair of satellites may be appealing, it must be implemented effectively in order to make it a viable, effective venture. Unless the facilities are adequate, the venture is effectively managed, and the policies and priorities are consistent with those of the commercial satellite industry, the scenario will most likely not be successful.

4 Summary of Interviews

A series of observations, conclusions, and recommendations can be drawn from our insurance industry interviews. These should outline the areas of concern to the insurance industry, and steps that should be taken to address issues of concern to the insurance industry.

- The insurance industry has historically been concerned about the introduction of new technologies. The Space Station can temper this concern by utilizing as much proven, existing technology as is consistent with safety, performance, and cost considerations.

- One effective method for assuring the satellite insurance industry that the satellite assembly and repair capability is reliable and cost effective is to use it for actual assembly, repair, and deployment on uninsured payloads such as future generations of GOES, TDRSS, or other government satellites. Although this approach may appear to be risky for the U. S. Government, it can be considered a key step in the creation of the satellite servicing facility. Once this scenario has been tested and satisfactorily demonstrated, the insurance industry may be willing to provide reduced rates.

- Until the assembly and repair of satellites becomes commonplace, customers can expect insurance rates to fluctuate significantly in response to both successes and failures.

- It will be important to keep the insurance industry involved throughout the long planning stages of this initiative. New issues can then be raised and clarified throughout the entire process. Concurrence from the insurance industry from the outset can help to structure the initiative to avoid insurance problems once the facility is operational.

- It will require a major selling job on the part of NASA and the rest of the U.S. government to promote this scenario and convince satellite manufacturers, satellite owners and operators, and the insurance community that on-orbit assembly, repair, and upgrade of satellites is desirable from both a technical and a cost standpoint.

- The general issue of Space Station liability and other insurance issues must be addressed and resolved. Every insurance executive with whom we spoke raised these issues during our conversations as areas of concern to the insurance industry.

- The insurance industry will probably not be a leader in providing an incentive to encouraging industry to design modular satellites. It will, however, support the scenario and provide insurance coverage at decreasing rates as the reliability of the launch, assembly, repair, and on-orbit transport of satellites is demonstrated.

- It is possible that future increased launch vehicle reliability will lead to a reduced role for insurance in determining the cost and feasibility of a space venture. However, it would be extremely short-sighted to plan for such a situation. It should be assumed that the high risk space environment will continue to foster an industry where insurance rates are a significant portion of total product cost.

- NASA should monitor the trend towards smaller satellites with co-orbiting duplicates. This potential trend was born out of the desire to reduce the risk associated with launch by lowering the cost of an individual satellite and maintain continuity of service in case of an on-orbit failure.

The insurance industry can not be expected to provide clear direction to the initiative to provide on-orbit assembly and repair of satellites. It clearly will not be the vehicle to force the satellite industry to redesign satellites to meet the modular construction characteristics for Space Station assembly and repair. The insurance industry appears to be ready to support efforts to reduce costs and risk pursued by the satellite industry. It may, ultimately, even play a large part in implementing the capability for satellite servicing, but does not appear to be ready to take the lead in pushing the concept. Overall rate reductions under this scenario are possible, but they will be realized only after the success and reliability of the entire assembly and repair effort are proven.